

**ASSESSMENT AND OPTIMIZATION OF INTEGRATED UNMANNED
AERIAL VEHICLES WITH DIFFERENT RENEWABLE ENERGY
SOURCES**

BY

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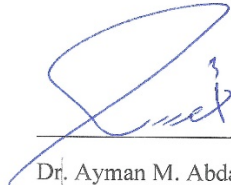
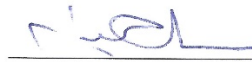
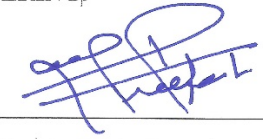
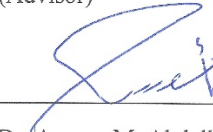
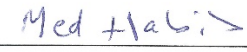
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| I dedicate this thesis work to my dear mother, father, and family. |

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LIST OF ABBREVIATIONS

E_G	Band gap energy
λ	Tunable parameter
γ	Parametric coefficient
β	Parametric coefficient
l	Membrane thickness (micro-m)
ρ	Density
η_p	Propeller efficiency
Zn-O ₂	Zinc oxide
W _{to}	Take-off weight
V _T	Thermal voltage
V _s	Stall velocity
V _{oc}	Output open circuit voltage of PV
V _{cr}	Cruise speed
UAV	Unmanned aerial vehicle
T _{PEM}	PEM typical temperature

T_{cell}	Cell temperature
S_w	Wing area
SPMS	Solar power management system
SOFC	Solid oxide fuel cell
SOC	State of charge
SFC	Smart fuel cell
SC	Solar cell
S	Wing surface area
S	Membrane surface area (cm^2)
R_s	Equivalent series resistance
R_m	Equivalent membrane resistance
R_{hc}	Vapor relative humidity at cathode
R_{ha}	Vapor relative humidity at anode
R_c	Concentration resistance
RC	Rate of climb
R_{int}	Internal resistance
Q	Battery capacity

q	Dynamic pressure
PV	Photovoltaic
Pt	Platinum
P_r	Hover power
PEMFC	Proton exchange membrane fuel cell
P_c	Inlet pressure for cathode
Pb-acid	Lead acid
PAFC	Phosphoric acid fuel cell
P_a	Inlet pressure for anode
O_2	Oxygen
N_R	Number of rotors
N_{nc}	Number for series connected cells of the PEMFC
NiMH	Nickel metal hydride
NiCad	Nickel cadmium
Ni	Nickel
MTOW	Maximum take-off weight
MPPT	Maximum power point tracking

MEA	Membrane electrode assembly
MCFC	Molten carbonate fuel cell
MALE	Medium altitude, long endurance
M	Figure of merit of the rotor
Li-SOCl ₂	Lithium-thionyl-chloride
Li-Po	Lithium polymer
Li-ion	Lithium ion
Li-air	Lithium-air
LHV	Low heating value
L/D	Lift-to-drag ratio
KOH	Potassium hydroxide
K _B	Battery capacity offset factor
k	Current temperature coefficient A/°C
K	Polarization constant (V/Ah)
J _{max}	Maximum current density (A/cm ²)
J	Actual current density (A/cm ²)
<i>it</i>	Actual charge

I_{pv}	Equivalent photocurrent
I_{PEM}	PEMFC operational current
I_o	Reverse current saturation
ICE	Internal combustion engine
$I_{sc,ref}$	Standards short-circuit current
HALE	High altitude, long endurance
H_3PO_4	Phosphoric acid
H_2	Hydrogen
GA	Genetic algorithm
G	Irradiance
FPE	Free piston engine
FCM	Fuel cell model
FC	Fuel cell
E_{ops}	Over-potential saturation in cells
E_{op}	Activation over-potential of the cells
E_{oc}	Open circuit potential condition per cell
E_O	Ohmic voltage drop in each cell

EMS	Energy management strategy
ED _h	Energy density of hydrogen
E ₀	Battery constant voltage
DMFC	Direct methanol fuel cell
DC	Direct current
DARPA	Defense advanced research projects agency
CO ₂	Carbon dioxide poisoning
C _L	Lift-coefficient
CFD	Computational fluid dynamics
CD	Drag coefficient
CAGR	Compound annual growth rate
B	Time constant for the exponential area (Ah) ⁻¹
AR	Aspect ratio
AFC	Alkaline fuel cell
AC	Alternative current
<i>a</i>	Factor coefficient
3-D	Three dimensional

ρ_m	Membrane specific resistance (ohm.cm)
η_R	rotor figure of merit
r_P	radius of propeller
V_{nom}	Rated battery voltage
P_{O_2}	Oxygen partial pressure (atm)
P_{H_2O}	Water partial pressure (atm)
P_{H_2}	Hydrogen partial pressure (atm)
I_{PH}	Photonic current generated by irradiance
I_P	Parallel resistance current
I_D	Diode current
C_{nom}	Rated battery charge
C_{O_2}	Oxygen concentration in the cathode's catalytic interface mol/cm ³
C_{H_2}	Hydrogen concentration in the cathode's catalytic interface mol/cm ³

|

ABSTRACT

Full Name : [Gubran Ahmed Qaid Abdulrahman]
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Renewable energy sources have been attracting great attention these days to minimize greenhouse gases (produced from fossil fuel burning) and secure the needed power for industrial and human activities. The literature showed a great potential to use renewable energy in aerospace vehicles, including unmanned aerial vehicles (UAVs). This thesis aims to evaluate and optimize different renewable and clean power sources for driving UAVs. These sources include fuel cells, batteries, and photovoltaic (PV) solar cells. Only fixed-wing UAVs type is investigated and evaluated. The fuel cell system is implemented into small fixed-wing UAV. The solar cell propulsion system is limited only to fixed wing UAVs, especially those with long wingspan. The study will focus on UAVs' main design and performance factors, such as power efficiency, endurance, and size. In addition, the integration of two or more power sources, such as fuel cells and batteries; fuel cells and PV cells; and fuel cells, batteries, and PV cells will be assessed. Each powering system is mathematically investigated to be integrated into UAVs to estimate the desired performance. This study suggests optimized powering sources for different sizes of UAVs. The results indicated that the fuel cell power source could achieve higher endurance time than the batteries. Fuel cells can be the best option for small fixed-wing UAVs. The battery power source has the lowest endurance time, and they are more suitable for mini and very

small drones. For the solar cell power cell, it is only suitable for fixed-wing UAVs, and it can have double flight endurance than batteries. Hybrid solar can last more than 48 hours, and they receive unlimited energy from the sun. Hybrid systems are heavy and bulky. |

ملخص الرسالة

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التخصص: هندسة الطيران والفضاء

تاريخ الدرجة العلمية: ماجستير

تجذب مصادر الطاقة المتجددة اهتمامًا كبيرًا هذه الأيام لتقليل غازات الاحتباس الحراري (الناجمة عن حرق الوقود الأحفوري) وتأمين الطاقة اللازمة للأنشطة الصناعية والبشرية. أظهرت الدراسات البحثية إمكانية كبيرة لاستخدام الطاقة المتجددة في مركبات الطيران والفضاء بما في ذلك الطائرات المسيرة بدون طيار (UAVs). تهدف هذه الأطروحة إلى تقييم وتحسين مصادر الطاقة المتجددة والنظيفة المختلفة لاستخدامها في تشغيل الطائرات بدون طيار. تشمل هذه المصادر خلايا الوقود والبطاريات والخلايا الشمسية الكهروضوئية. تمت دراسة نظام خلايا الوقود في الطائرات بدون طيار الصغيرة ذات الأجنحة الثابتة. يقتصر نظام دفع الخلايا الشمسية على الطائرات بدون طيار ذات الأجنحة الثابتة ، خاصة تلك التي تمتلك أجنحة طويلة. تركز الدراسة على عوامل التصميم الرئيسية والأداء للطائرات بدون طيار مثل كفاءة الطاقة والقدرة ومدة الطيران. بالإضافة إلى ذلك ، دمج مصدرين أو أكثر من مصادر الطاقة مثل خلايا الوقود والبطاريات ؛ أو خلايا الوقود والخلايا الكهروضوئية ؛ أو خلايا الوقود والبطاريات والخلايا الكهروضوئية معا. تم مناقشة وتقصى كل نظام طاقة رياضيًا ل يتم دمجها في الطائرات بدون طيار لتقدير الأداء المطلوب. تقترح هذه الدراسة مصادر طاقة محسنة لأحجام مختلفة من الطائرات بدون طيار. أشارت النتائج إلى أن مصدر طاقة خلية الوقود يمكن أن يحقق وقت طيران أعلى من البطاريات. يمكن أن تكون خلايا الوقود الخيار الأفضل للطائرات بدون طيار الصغيرة ذات الأجنحة الثابتة ، ولديها أداء أفضل من البطاريات إذا تم استخدامها في الطائرات بدون طيار منخفضة المدى. استخدام البطاريات يعطي أقل وقت طيران ، وهو أكثر ملاءمة للطائرات بدون طيار الصغيرة والصغيرة جدًا. بالنسبة لأداء الخلايا الشمسية ، فهي مناسبة فقط للطائرات بدون طيار ذات الأجنحة الثابتة ، ويمكن أن تزيد في وقت الطيران ضعف ما لدى البطاريات. يمكن أن تدوم الطاقة الشمسية الهجينة أكثر من 48 ساعة ، وتتلقى طاقة غير محدودة من الشمس. إلا أن الأنظمة الهجينة ثقيلة وضخمة الحجم.

CHAPTER 1

INTRODUCTION

Encouraged by recent technical advancements, unmanned aerial vehicles (UAVs) have witnessed a remarkable increase in interest in recent years and are now regarded as a vital and essential element of contemporary military forces [1], with a rising number of double use and civil applications. UAVs use different types of propulsion systems such as combustion engines, batteries, fuel cells (FCs), solar power, etc. Each one of these power systems has its own advantages and disadvantages. Energy and power densities are used to define most UAV propulsion systems. The power density of a source determines the quantity of power it can supply at any one time, whereas the energy density determines the amount of energy it can store and how long can that amount of power be given [2]. Fuel cells and batteries are utilized as a propulsion system for UAVs and as a backup power unit for airplanes[3,4]. Fuel cells have high specific energy and, therefore, a high efficiency, which makes them useful in the aerospace and automobile industries [5].

A few fuel cell-based UAVs and civil aircrafts have been tested [6–9]. Most of the research on fuel cells in airplanes is purely theoretical. Only a few studies [10–14] examined the use of FCs on lightweight or ultralight aircraft, where batteries are normally favored. However, batteries have several disadvantages, the most significant of which is the low power and energy density, or the power and energy per unit mass and volume. Furthermore, several

parameters such as discharging and recharging currents, as well as operating temperature, impact the capacity and lifetimes of batteries [15]. Lately, substantial work has been devoted to comparing the two existing technologies for UAVs (batteries and fuel cells)[16–19]. The comparison necessitates an accurate assessment of durability as well as consideration of the quantity of energy stored onboard. It's worth noting that batteries store energy as electricity, whereas fuel cells store energy as pressurized gaseous fuel.

A solar cell, like fuel cell devices, is a rapidly growing renewable power source that turns sunlight directly into electricity which can be used for a variety of purposes. The mobility industry, which includes UAVs, is a prominent application. That's because the solar-powered airplane is propelled by an electrical propulsion system that is low-cost, ecologically friendly, highly energy-efficient, and fueled by infinite sunlight [20,21].

This thesis study evaluates the utilization of renewable and clean power sources to drive rotary and fixed-wing UAVs, including fuel cells, batteries, and solar panels. The study will compare the performance of each power source, such as the utilization of the hybrid power system. The fuel cell is integrated with a small fixed-wing UAVs, while the battery is integrated with rotary drone. The solar cell system is limited to fixed wing UAVs, and it is the best option for long range and large UAVs compared to fuel cells and batteries. Additionally, the study presents an optimization technique to obtain the best model to power UAVs. The optimization includes output power, flight efficiency, and flight endurance of a UAV. Different mathematical models of fuel cells, batteries, and solar cells are utilized after being validated against some reported experimental data to assess and evaluate renewable energy-driven UAVs.

1.1 Objectives

This thesis aims to assess and optimize the integration of UAVs with renewable and clean energy sources. Renewable energy sources include fuel cells, batteries, and photovoltaic solar cells. Additionally, a hybrid power system of more than one propulsion system (such as fuel cells/batteries, fuel cells/PV cells) will be investigated.

The detailed objectives of this study are as follows:

- Evaluate different clean and renewable power sources that are used to drive UAVs, including batteries, fuel cells, and PV cells.
- Develop a mathematical model for integrated UAVs with renewable energy sources.
- Investigate the integration of one or more power sources to efficiently derive various types of UAVs.
- Optimize the design and performance indicators of UAVs based on one or more of the used renewable power sources.
- Map the appropriate power system for various UAVs based on the performance indicators. |

CHAPTER 2

LITERATURE REVIEW

Sufficient recent literature concerning the UAVs' propulsion system powered by fuel cells, batteries, solar cells, or hybrid systems is proposed. The literature includes a classification of UAVs and their renewable power sources. A critical review of FC technique included the fundamental principles, history, types, applications, and modeling. Furthermore, the review discussed electrical UAVs driven by batteries, including the most common batteries used for powering UAVs. Solar cells-based UAVs are discussed as well. Additionally, the literature will introduce a hybridization propulsion system of UAVs, including the integration of fuel cells with batteries, the fuel cell with PV panels, and the integration of the three systems (fuel cell, battery, and solar cells). The literature reviews different characteristics of the performance of each system, such as flight endurance, output power, overall efficiency, power management system, modeling, etc.

2.1 UAVs Classifications

UAVs can be categorized based on three parameters, including geometry, size (e.g., micro, very small, small and large), mass, and mission such as HALE, MALE (see Table 1). There are three types of UAVs based on geometry which are fixed-wing, rotary-wing, and a combination of fixed and rotary wing (Figure 1). The rotary UAV is made up of a body that moves by using several rotors. They have the appearance of fixed wings in a conventional airplane. Rotorcrafts are increasingly common since they can take off and land vertically, eliminating the need for a runway or any sort of launcher technology. They are highly nimble,

which makes them ideal for precise maneuverability purposes. However, rotary UAVs have complex mechanical and electrical systems, which results in decreasing operating time, high-cost maintenance, and increasing expenses. Rotary UAVs have additional drawback of having lesser load capacity, which increases power needs, decreases operational time, and raises prices further [2].

Fixed-wing UAVs have a simpler geometry and construction than rotary types. Their simple configuration improves aerodynamic efficiency and increases flight endurance. They also have less operational time cost and simpler maintenance. In addition, fixed-wing UAVs provide an ability for natural gliding and hence less power consumption, while the UAV will be able to carry more weight for a long distance utilizing less power consumption. Unlike the rotary types, the fixed-wing types need runway or launcher devices for landing and take-off. They are much larger and bulkier than the rotary types, and they are not able to hover, which makes their maneuverability a hard task [22].

Another type of UAV that consists of both rotary and fixed wings (Figure 2). It combines the flexibility and stability of rotary-wing UAVs with the extended flying range of fixed wing UAVs. Moreover, there is no need for any launcher device or runway.

Fixed-wing UAV



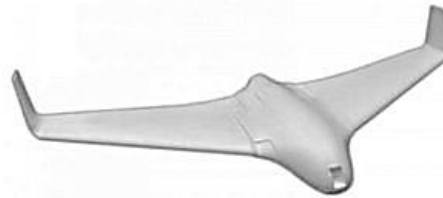
Bormatec Maja



Bormatec Explorer



CyberEye II



Skywalker X8

Rotary-wing UAV



T-REX 700E



DJI Matrice 600



AirRobot AR100B



AscTec Falcon 8

Figure 1. Fixed and rotary UAVs [23].

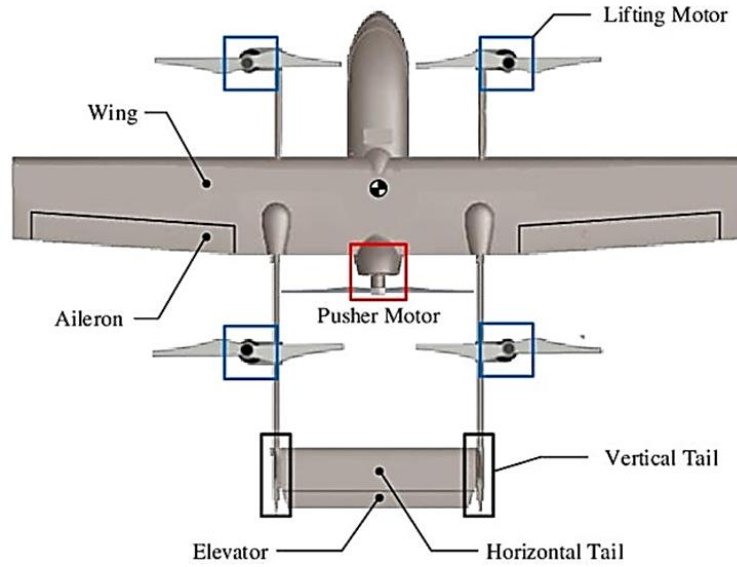


Figure 2. Example of combined fixed and rotary-wing UAV [24].

Table 1. Different UAVs classifications [25].

Sr. No	UAV category	Weight (lb)	size	Range (km)	Endurance	Altitude (kft)
1	Micro	< 0.55	≥ 10 cm	0.1 – 0.5	≤ 1 hr	< 0.1
2	Mini	0.55-2	10–30 cm	0.5 –1	≤ 1 hr	< 0.5
3	Very small	2-5	30 –50 cm	1 –5	1-3 hrs.	< 1
4	Small	5-55	0.5 –2 m	10 –100	0.5-2 hrs.	1 –5
5	Medium	55-1000	5 –10 m	500 –2000	3-10 hrs.	10 –15

6	Large	1000- 30000	20 –50 m	1000 – 5000	10-20 hrs.	20 –40
7	Tactical combat	1000- 20000	10 –30 m	500 –2000	5-12 hrs.	10 –30
8	MALE ^a	1000- 10000	15 –40 m	20000 – 40000	20-40 hrs.	15 –30
9	HALE ^b	> 5000	20 –50 m	20000 – 40000	30-50 hrs.	50 –70
10	Quadcopter	0.5-100	0.1 – 1 m	0.1 – 2	20 min – 1 hr.	< 0.5
11	Helicopter	0.001-200	13 –2 mm	0.2 –5	10 mins – 2 hrs.	< 500

^a MALE: Medium Altitude, Long Endurance

^b HALE: High Altitude, Long Endurance

2.2 UAVs Driven by Fuel Cells

Unlike heat engines, fuel cells employ an electrochemical process to generate electricity from the chemical energy contained in the hydrogen fuel [26]. Fuel cells directly convert fuel into electricity, making them more efficient than combustion engines. The amount of power produced by a fuel cell is only limited by the amount of fuel available. The maximum current produced by a fuel cell is determined by the number of cells connected in series and the required voltage [26]. Fuel cells are a reliable and efficient renewable energy source that uses

an electrochemical process to continuously convert hydrogen fuel into electricity [27,28]. Fuel cells have recently been significantly developed and commercially accessible for applications in the high, medium, and low power ranges. Researchers have been focusing on improving the reliability and efficiency of fuel cell-based power systems to minimize the cost of fuel cells [29,30].

Lifetime and cost are the two most significant barriers to fuel cell commercialization [31]. A fuel cell used in a commercial setting can operate for a long time without significant degradation. In lightweight vehicles, it can last for more than 5000 hours of use, while in stationary power applications it can last for over 40,000 hours. The degradation, or decline in performance, is typically less than 10% over the course of its lifetime [32,33]. In order to address the challenges and advance the development of fuel cell technology, it is important to have a thorough understanding of how fuel cells work and to stay up to date on the fuel cell industry. This will help to overcome the current difficulties and support the growth of this technology. Nonetheless, fuel cells are a multidisciplinary discipline that combines electrochemistry, thermodynamics, engineering economics, material science and engineering, and electrical engineering, making this a challenging task [34]. Many comprehensive reviews about FCs technology, applications, operation, and limitations are highlighted in [30,34–39].

2.3 Fundamental of Fuel Cells

The fuel cell has a simple working principle, but it has a sophisticated design. Fuel cells consist of a cathode, anode, electrolyte, and fuel. The cathode and anode are the positive and negative terminals, respectively. The electrolyte within and the exterior electric circuit are

connected by these two terminals [30]. The anode receives fuel on a continual basis, whereas the cathode receives an oxidant. The fuel is usually pure hydrogen or a mixture of hydrogen gases such as methanol, ethanol, and natural gases. The oxidants are either pure oxygen or oxygen gases such as air or halogens such as chlorine[40,41].

In a fuel cell, the hydrogen combustion reaction is split into two electrochemical half-reactions:

Anode reaction:



Cathode reaction:



Overall reaction:



H₂ produces ions (H⁺) and electrons (e⁻) as a result of the anode reaction. The H⁺ moves directly to the cathode, while the e⁻ moves to the cathode via the load (external circuit). Finally, H⁺ and e⁻ combine with oxygen (O₂) to produce water, which is a fuel cell benefit [42].

2.4 History of Fuel Cells

The early 1800s saw the beginning of studies and developments that led to the creation of a fuel cell. In 1839, Sir William Grove, a chemist and patent lawyer, is often regarded as the "Father of Fuel Cell Science" because of his famous water electrolyzer/fuel cell experimental

demonstration. Sir William Grove utilized his electrolysis experience to imagine a reverse process that might be used to create electricity. Charles Langer and Ludwig Mond, who investigated fuel cells utilizing coal gas as a fuel, coined the name "fuel cell" in 1889. In the early twentieth century, there were more attempts to convert coal directly into electricity, but the technique remained mostly unknown. Francis Bacon developed the first alkaline fuel cell AFC at the beginning of the 1900s. NASA began researching fuel cell generators for human space flights in the late 1950s and early 1960s. Willard Thomas Grubb's developed first PEM fuel cell, which used platinum as a catalyst on the membranes, was one of the earliest PEMFC units. Fuel cells have found a variety of uses, including in transportation, stationary systems, and portable devices. Both public and private industries have been increasingly adopting fuel cells due to their improved durability and reliability for long-term operation. These cells can function using either air or hydrogen as an oxidant and fuel, respectively, through a process known as reformation. In 2008, fuel cell technology became commercially available in many different applications. Figure 3 summarizes the main important milestones of fuel cells development.

The History of Fuel Cells

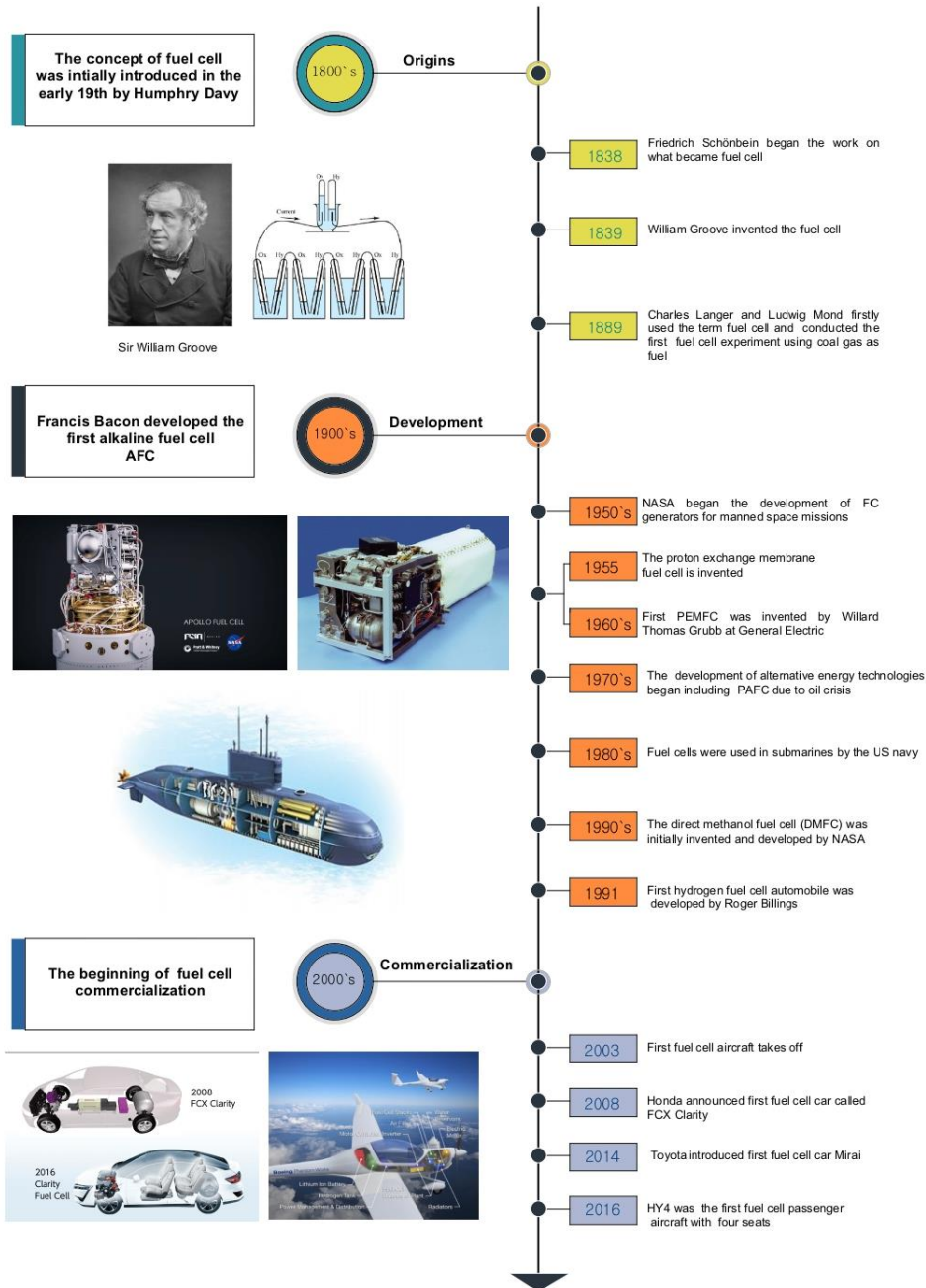


Figure 3. History of the fuel cell (origins, developments, and commercialization).

2.5 Types of Fuel Cells

Fuel cells are usually categorized based on the electrolyte or fuel type used. There are several sorts of FCs, and each one has its own chemistry (catalyst and electrolyte) and operational properties (e.g., temperature). Here are descriptions of the most popular fuel cells on the market.

- Proton Exchange Membrane Fuel Cell

The proton exchange membrane fuel cell (PEMFC) is an incomparable option of interest among various types, particularly in the fields of automotive studies, delivered generation, and transportable devices applications [43–45]. PEMFC is also unique because of its distinguishing properties, which include simplicity, lightweight, high efficiency, high power density, no waste production, low operating temperature (below 100°C), and pressure [35,46]. This makes PEMFCs the most co-fuel cells used for aircraft propulsion and hence highly suited for flight demands [47]. Furthermore, compared with other types of fuel cells, the better technological maturity and lower cost match the criteria of long-range UAVs. For power ranges between 100W and more, the typical efficiency of a PEMFC ranges from 40–60 percent [34,47] and is only significantly impacted by size. Furthermore, peak efficiency occurs when the system is just partially loaded. Heat engines, on the other hand, lose efficiency quickly at low power levels and component loads [48–50].

A PEMFC system's specific power may approach 150 W/kg, and multiple test flights have shown that tiny PEMFCs may be used in UAVs, despite most of these flights having been tested for studies or illustration reasons [35]. A PEMFC has a basic structure that consists of an anode and cathode separated by a solid polymer membrane electrolyte. The hydrogen fuel

is delivered to the anode through a series of channels, where it is broken down into protons. These protons then travel through the membrane to the cathode[51]. An external circuit connecting the two electrodes collects the electrons, creating an electrical current. The oxidant, such as oxygen from the air, is delivered to the cathode through a series of channels similar to those in the anode. At the cathode, the oxygen reacts with the electrons from the external circuit and the protons flowing through the electrolyte membrane to produce water and heat [52–54]. Figure 4 shows a typical PEMFC scheme with its chemical process.

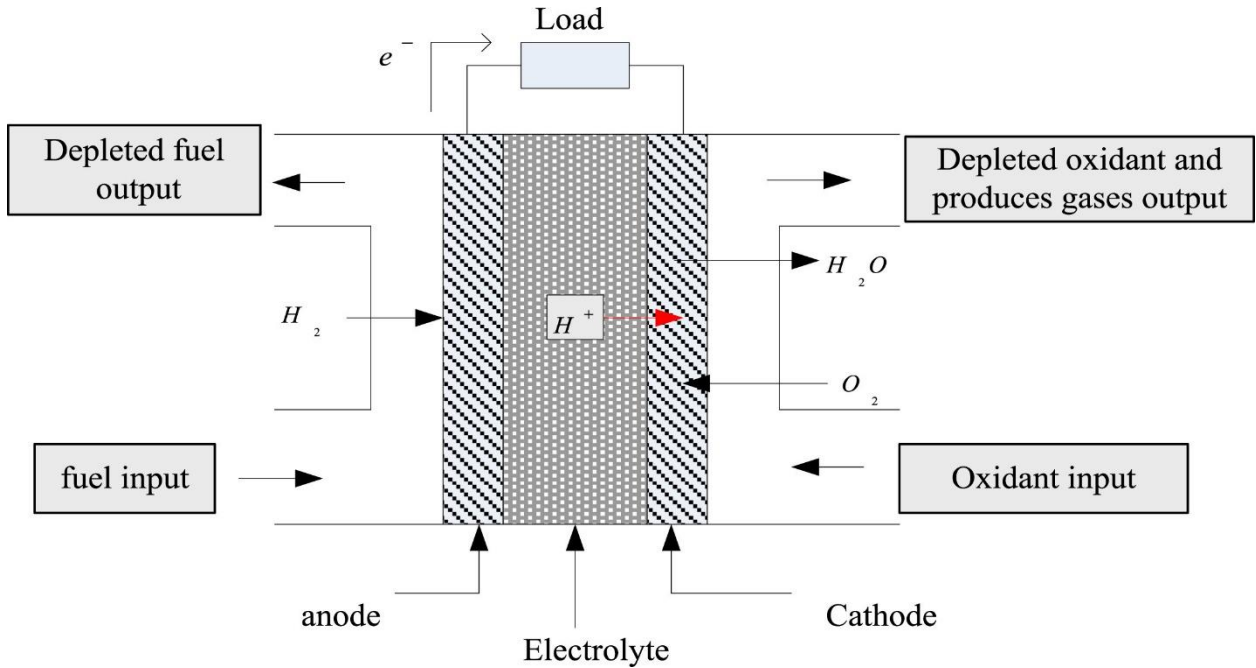


Figure 4. PEMFC basic operation [37,55].

Fuel cell models (FCMs) are crucial in PEM fuel cell development because they aid in comprehending the electrochemical reaction, thermodynamic phenomena, and fluid transfer mechanism in PEM fuel cells. In recent years, several fuel cell modeling (FCM) approaches using computational fluid dynamics (CFD) software have been developed to analyze multi-phase, multi-component, multi-dimensional flow, heat, and mass transfer

in conjunction with the electrochemical reactions that occur in complex geometries, such as in porous media [56,57]. These models are highly useful in studying the transport mechanism of PEMFC, flow field design, and thermal and water management.

It is difficult to model the features of PEMFC systems for design and performance evaluation since they are complicated, multimodal, and strongly connected. Through mathematical modeling, great development has been achieved in understanding the behavior of PEMFC features over the decades [52,55,58–63]. To make optimal use of these devices, mathematical models of the vehicle fuel cell stack are required so that the system behavior can be analyzed at the design stage using computational simulations under various load, reagent gas pressure, and temperature conditions [64]. Meanwhile, in the context of analysis, design, simulation, and development of excellent-efficiency fuel cells, modeling is becoming increasingly important. Despite the existence of several modeling methodologies, mathematical modeling introduced by Amphlett [65] gained recognition due to its accuracy in forecasting PEMFC performance under various operating situations. Most models in literature are supported by experimental results. The most common approach to validation is to evaluate and compare the polarization curve obtained by both mathematical and experimental inquiries. The model is regarded as trustworthy if two polarization curves have the same or close results [66]. The performance of a bench-size hydrogen/air fuel cell stack is experimentally determined for various airflow rates and temperatures [67]. The experimental data is utilized to calculate the mathematical model parameters that explain the polarization curve. Because of the complexity and non-linearity of the transportation processes and systematic

properties, mathematical modeling is excellent for designing PEMEC [68,69]. Models that have been thoroughly designed and validated undertake a sensitivity analysis of design and give optimized operational conditions.

The PEM electrolyzer performance is continuously improving, and it is on the commercialization path. Two comprehensive reviews [70,71] have offered a thorough examination of PEM electrolysis methods and the current state of research. The reviews cover the material, components, and modeling of PEM electrolyzers, as well as the approach and importance of modeling in enhancing PEM electrolyzer performance. Multi-physics and multiscale techniques are used in PEMEC modeling, which ranges from catalytic and membrane/electrode electrochemical processes through the performance of the cell or stack multi-dimensionality may be used in PEMEC models incorporating thermal-flow distributions, varying from a 0-dimensional model to 1-dimensional, 2-dimensional, and 3-dimensional model. While one-dimensional and two-dimensional models can explain physical phenomena in such detail, three-dimensional models depict the system and components. Moreover, the membrane electrode assembly (MEA) components and flow fields' transport phenomena are intrinsically 3-D [71]. simulations can be divided into two categories: steady-state and dynamic. A steady-state model assumes that all state variables are constant over time and can be used to evaluate the overall performance of a fuel cell or stack. These models are often used in material studies and property simulations and are generally easier to solve numerically due to their stable nature. They aid in the development of physical and chemical foundations for models of various sizes and scopes. The transport processes in the proton-conductive

membrane have been fully researched in [68,69,72–74], and they are one key subject for modeling.

Priya et al. [37] evaluated the modeling methodologies as well as the available research on fuel cell parameters extraction methods. The topic ranged from the traditional Genetic Method to the more current Grey Wolf algorithm. Additionally, a critical assessment was carried out based on algorithm complexity, Objective function, V-I characteristics matching, parameter adjustment, and computational performance. Saadi et al. [75] compared the various analytical methods for modeling PEMFC stacks. Three static models are presented, including those of Chamberlin–Kim [76], Amphlett [77], and Larminie–Dicks [47]. These models are investigated and validated empirically, with their parameters identified independently. As a result, the experimental findings compared two rated powers (400 W and 700 W) in the fuel cell. Furthermore, the correctness and effectiveness of these static models are explicitly verified by simulation results.

- Direct Methanol Fuel Cells

Direct methanol fuel cells (DMFCs) are one of the most promising power alternatives for portable electronics, small-range vehicles, and military applications because they transform chemical energy from liquid fuels to electrical energy via electrochemical processes [78–81]. The features of DMFCs include simple structure, high specific energy, high efficiency, and low emission [82]. However, the slow kinetics of the oxygen reduction reaction [83] in the cathode catalyst layer, as well as the high cost of the membrane electrode assembly (MEA) [84] make DMFC commercially less viable [85]. DMFCs are essentially identical to PEMFCs in construction and operate at low

temperatures [34], allowing for quick start-up and load following. The fuel, however, is methanol instead of hydrogen. Because of the high specific energy of DMFCs (up to 6000 W h kg⁻¹ for pure methanol), the DMFC system commercialization has been potentially increased in a wide range of applications, including laptop power supply, unmanned aerial vehicle power, single soldier power, and stationary power plants [81]. The stack power densities and system power densities of DMFC have been achieved 72 W/kg and 53.6 W/kg, respectively [86]. This is far less than proton exchange FC stacks, which have stack power densities of over 800 W/kg and system power densities of over 150 W/kg [26,87]. Additionally, methanol oxidation is a complicated process, with the anode reactions taking longer than with hydrogen [47,88]. This results in a lower power density. A DMFC's total efficiency ranges from 20 to 30%, nearly half that of a PEMFC [89]. As a result, more methanol must be transported in order to create the same quantity of energy. The formation of Platinum particle agglomerates in the typical cathode catalyst layer, which is made of Pt as a catalyst, carbon black as an electron conductor, and electrolyte as a proton conductor, is one of the technological obstacles [90,91]. Due to the low Pt usage, catalyst agglomerations cause a considerable loss in electrochemical surface area (ECSA) [92]. Pt efficiency in typical cathode catalyst layers is as low as 20–35 percent [93,94].

In the previous two decades, a few firms, such as UltraCell in the United States and Smart Fuel Cells (SFC) in Germany, have considerably developed the early commercialization of DMFCs with systems ranging from 25 to 1000 W [81]. Figure 5 shows the

configuration of a typical DMFC stack, including MEAs, bipolar plates, gaskets, and other accessories.

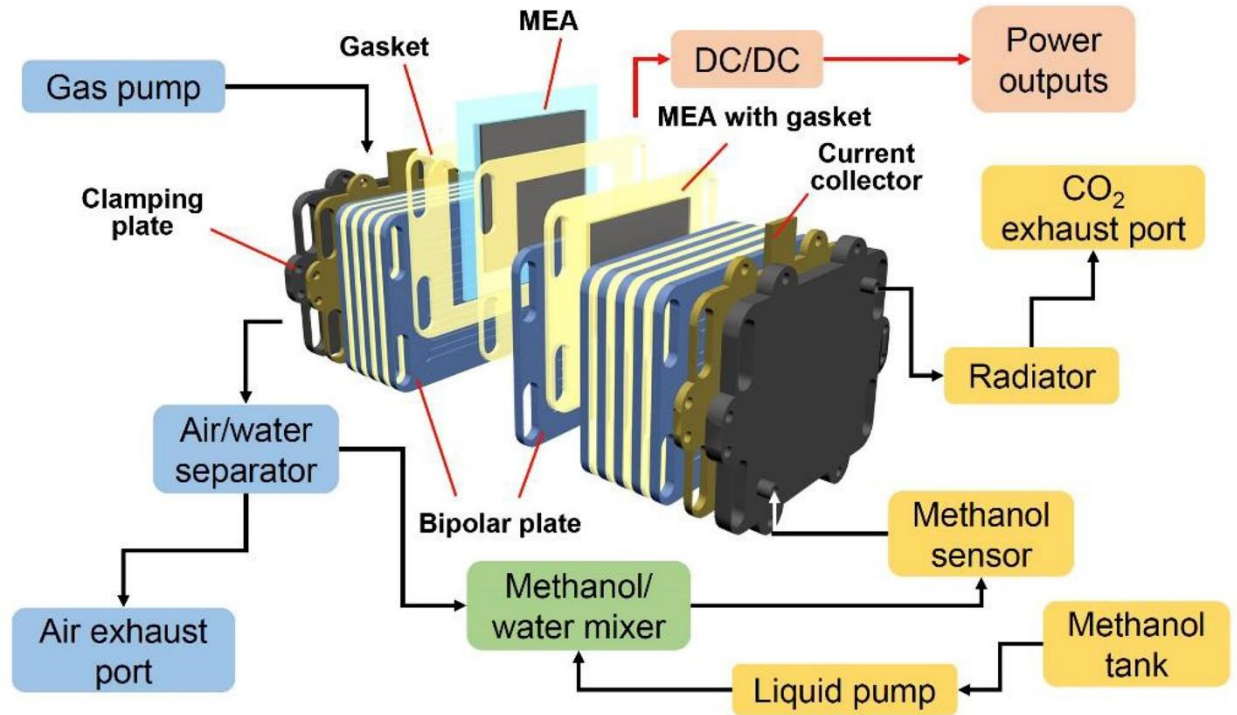
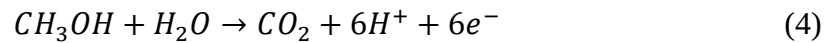


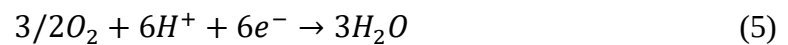
Figure 5. Typical DMFC stack and system configuration [81,95–98].

The chemical reactions of methanol and oxygen in the anode and cathode, respectively, are the essential principle of DMFCs, as shown by the equations below.

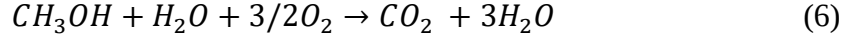
Anode reaction:



Cathode reaction:



Overall reaction:



At 25 °C, the DMFC thermodynamic potential is 1.21 V, and the methanol thermodynamic efficiency could reach 96.4% through the above electrochemical processes, which is significantly higher than that of the combustion engines limited by the Carnot cycle [81,99].

- Solid Oxide Fuel Cells

Solid oxide fuel cells (SOFCs) are a type of high-temperature fuel cell. The SOFC's electrolyte material is solid oxide, as the name implies, allowing it to operate at high temperatures between 600 and 1,000 degrees Celsius [100,101]. SOFCs may use hydrocarbon fuels like propane because of the high temperature, which enhances the availability of fuel and decreases storage requirements. These high temperatures, on the other hand, must be carefully regulated, and because SOFCs require time to warm up and achieve working temperature, they are unable to respond to (fast) load changes [34]. SOFCs have average efficiencies of 25–50 percent [26].

The reaction of fuel with an oxidant in a SOFC creates usable power by diffusion of oxide ions via an ion-conducting solid-electrolyte layer [102]. As illustrated in Figure 6, SOFCs are made up of a thick electrolyte layer sandwiched between the cathode and anode. An oxide ion (Figure 6 a) or proton conduction through the electrolyte can be used in the SOFC (Figure 6 b). The electrons created by the oxidation of fuel at the anode are received at the cathode for oxygen reduction, completing the external circuit. The passage of electrons in the external circuit, therefore, produces electricity [103].

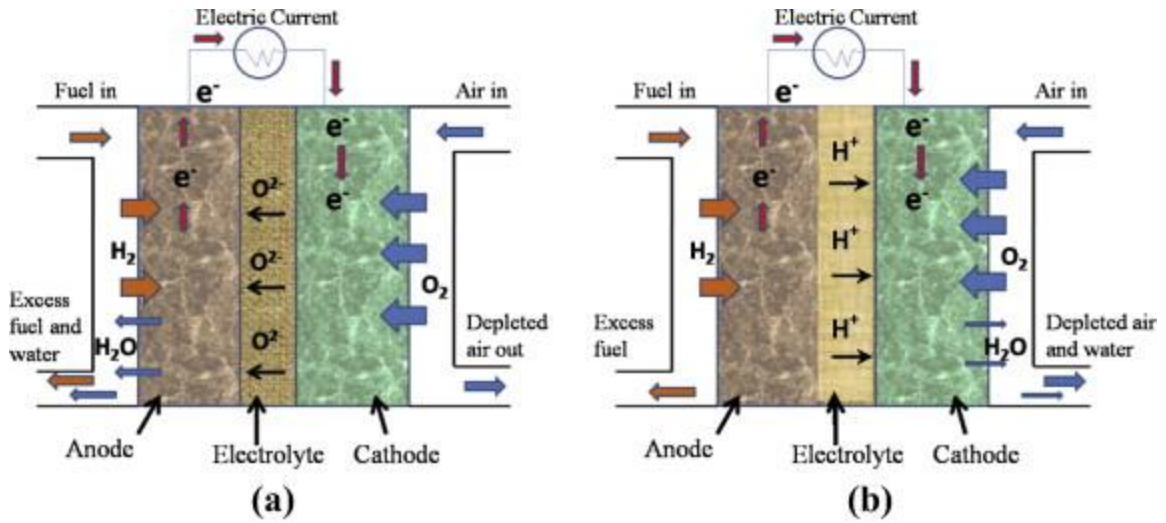


Figure 6. Schematic of SOFC: (a) oxide-ion conducting electrolyte, and (b) proton conducting electrolyte during its operation [103]

SOFCs have been widely investigated, including numerical simulations of computational fluid dynamics (CFD) [104,105] and experimental studies [106–108]. There are many initiatives involving SOFC mobile applications that are considered as a power system. The Defense Advanced Research Projects Agency (DARPA) [109] conducted a test of the stalker-XE UAV powered by solid oxide FC. The test resulted in a significant increase in UAV flight time, more than the endurance of vehicles driven by batteries. In addition, Giacoppo et al. [101] investigated a UAV driven by solid oxide FC with a cooling system, which was the same size as the stalker-XE UAV. Furthermore, Nissan [110] has created the world's first light-duty prototype car driven by a SOFC using bio-ethanol reformat as fuel and producing 5kW of electricity.

- Phosphoric Acid Fuel Cells

The most common and well-documented form of fuel cells is the phosphoric acid fuel cell (PAFC). More than 500 PAFC power stations have been built and tested across the globe since the 1970s. With each successive product release, the number of units sold increased, as did the power rating of each unit [111]. PAFCs are a technology that is classified as medium-temperature systems, and they use a liquid phosphoric acid (H_3PO_4) electrolyte and operate at temperatures ranging from 150 to 220 degrees Celsius [112,113]. The PAFC efficiency is also rather high; for example, the UTC PC25 fuel cell has a demonstrated net electrical efficiency of 37% and a total efficiency of 87 percent in Combined Heat and Power Applications when powered by natural gas. In comparison to typical power systems, this results in lower fuel consumption and lower pollutant emissions [111].

In a Teflon-bonded silicon carbide (SiC) structure, the electrolyte is an acid [114]. It allows hydrogen cations to flow to the cathode. At the anode, the electrons created during the reaction flow through an external circuit to the cathode, generating direct current (DC). At the cathode, water is produced as the electrons and hydrogen ions react with oxygen. The reactions that occur at the anode and cathode can be represented by the following equations:



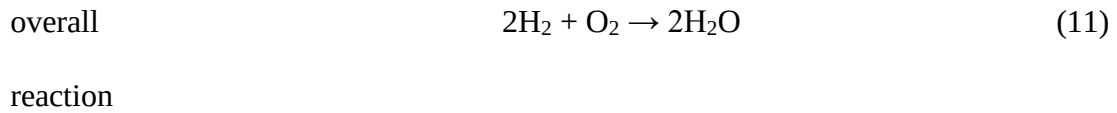
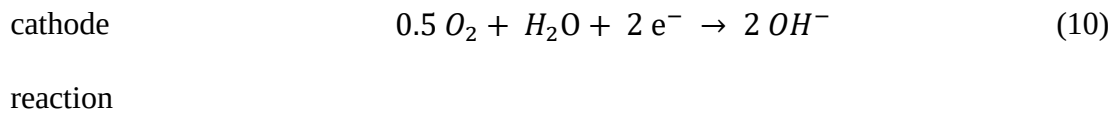
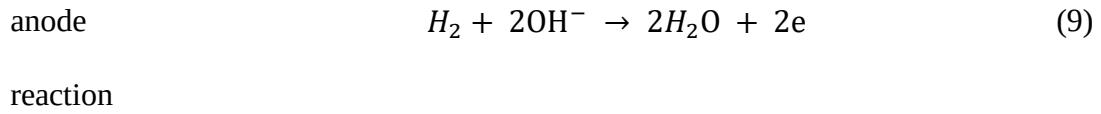


Further research on PAFCs is still required in order to enhance power density, extend life, and reduce manufacturing costs. PAFC's poor power density is a significant drawback that limits its widespread adoption [115]. Many experimental and theoretical research have been done in recent years to increase the power density of PAFCs, including material manufacturing [116,117], a better knowledge of electrochemical processes and transport phenomena [118–121], performance evaluation at the stack [122], or system level [123].

- Alkaline fuel cells

Alkaline fuel cells (AFCs) were among the earliest fuel cell technologies created, and they were the first type widely utilized in the United States space program to generate electricity and water onboard spacecraft. As the electrolyte in these fuel cells, a solution of potassium hydroxide in water is used, and several non-precious metals can be used as a catalyst at the anode and cathode [114]. They operate by supplying hydrogen fuel to the anode while transporting oxygen to the cathode. Ion exchange between the cathode and anode in liquid KOH is permitted, resulting in the production of direct current [113]. As “microporous” separators in alkaline FCs, materials such as potassium titanate, ceria, asbestos, and zirconium phosphate gel have been employed [124]. However, asbestos is no longer utilized because of its toxicity and health risks. The working temperatures of AFCs range from 100 C to 250 C, while modern devices have operating temperatures around 70 C, which is the reason to classify AFCs as low-temperature systems. Because of its low-temperature property, nickel (Ni) is often employed as the catalyst in alkaline

FCs instead of the usual platinum material [125]. The electrolyte in AFCs is an aqueous solution of potassium hydroxide, with about 30% of concentrations [126]. The overall chemical reaction of AFC is described by the following equation:



Byproducts such as heat and water must be eliminated. This is generally accomplished by recirculating the electrolyte and utilizing it as the cooling liquid while evaporation removes the water. Figure 7 depicts a schematic of the recirculating electrolyte AFC.

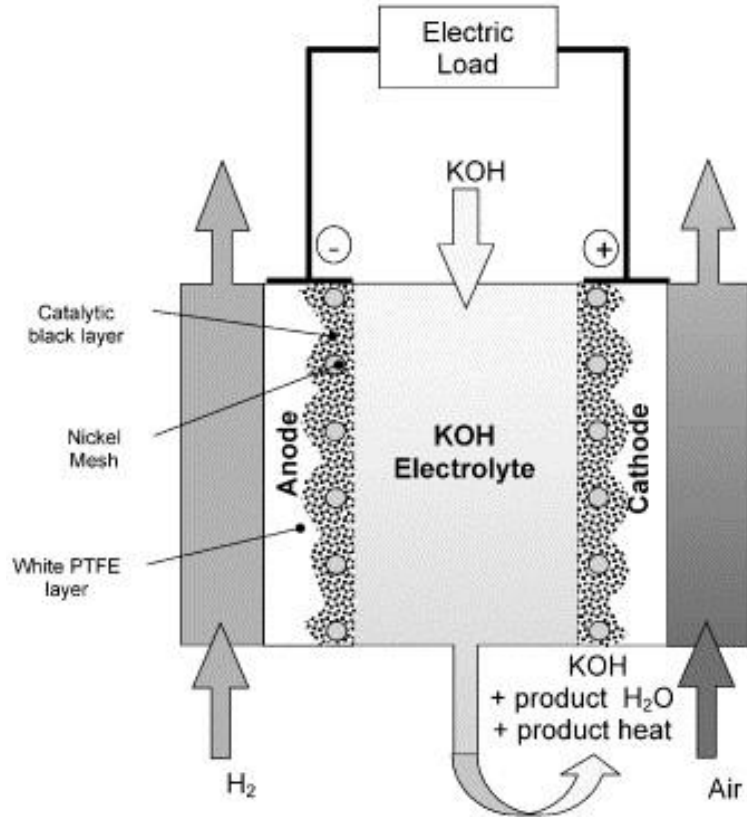


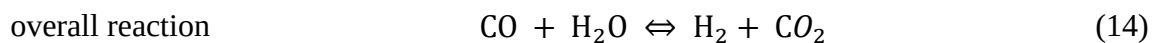
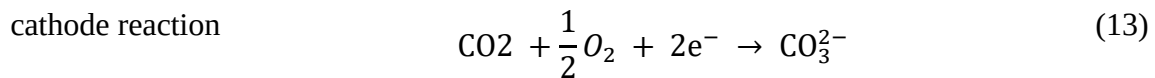
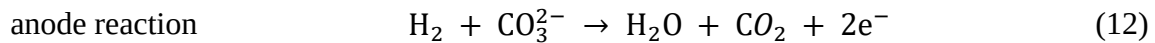
Figure 7. Alkaline fuel cell composition [126].

Alkaline FCs have the benefit of having a relatively high efficiency of up to 0.6 in specific applications [125]. The great performance of AFCs is related to the rate at which electrochemical reactions occur in the cell. In space applications, they have also achieved efficiencies of more than 60% [114]. Additionally, alkaline FCs may produce electrical output ranging from 5 to 150 kW [113]. One significant difficulty for alkaline fuel cells is that it is sensitive to carbon dioxide poisoning (CO₂). In fact, even a minor quantity of CO₂ in the air can have a significant impact on cell performance and durability owing to carbonate production [114].

- Molten Carbonate Fuel Cell

The molten carbonate fuel cell (MCFC) is considered as a high-temperature system (>600 °C) fuel cell that has already achieved commercial size with capabilities of several megawatts [127]. This technology is projected to be employed in stationary and distributed power production applications because of its high efficiency and minimal emission levels [128]. When combined with a turbine, MCFCs may achieve efficiencies of up to 65 percent, which is significantly greater than the 37 percent to 42 percent efficiencies of a phosphoric acid fuel cell system. Overall fuel efficiency can reach over 85% when waste heat is collected and utilized [114].

The carbonate electrolyte used in MCFCs is often a combination of lithium and potassium carbonates (salts). A ceramic electrolyte support mesh is used to support and wick the electrolyte materials, which become molten at ordinary working temperatures, to cover electrode surfaces (often LiAlO_2). The Ni–Cr/Ni–Al alloys are used in the anode, whereas the cathode materials are lithiated NiO. The operation of a fuel cell is the consequence of a complicated interplay of chemical, physical, and electrochemical processes [129]. The chemical reactions of MCFC are described by the following equations [127]:



The disadvantages of MCFC include a relatively sluggish oxygen reduction process, excessive bulkiness, corrosion, poor power density, durability, and high cost. The fuel flexibility and high working temperature of this fuel cell are advantages [114,130]. To minimize weight and size, high power densities must be created in the fuel cell.

2.6 Modeling UAVs Driven by Fuel Cells

A lot of studies have been conducted to investigate the hydrogen fuel cells that are used as a UAV propulsion system. Bradley et al. [14] developed a 500W PEM fuel cell powerplant which was integrated with UAV, shown in Figure 8. Three conditions were indicated in the study, including idle, high power, and nominal cruise. The study represented design requirements and control of UAVs as well as the fuel cell stack and specifications, as shown in Figure 9 and Figure 10.



Figure 8. Fuel cell UAV used in the study [14].

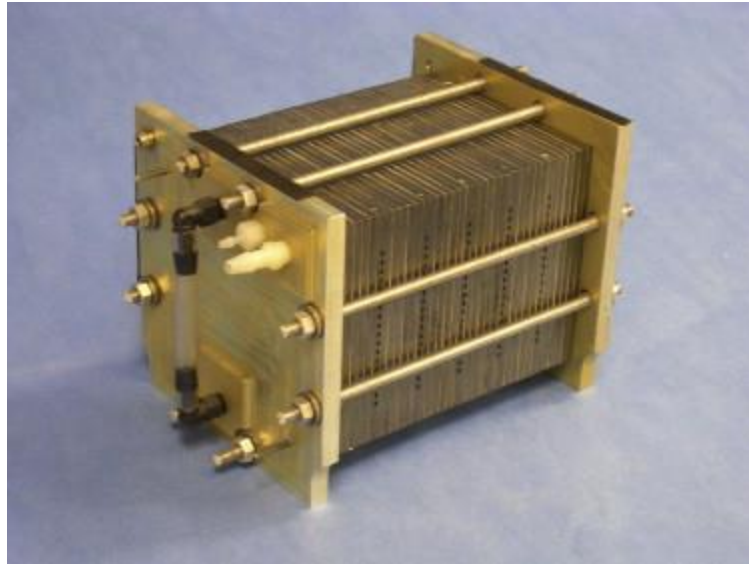


Figure 9. The model of the fuel cell stack [14].

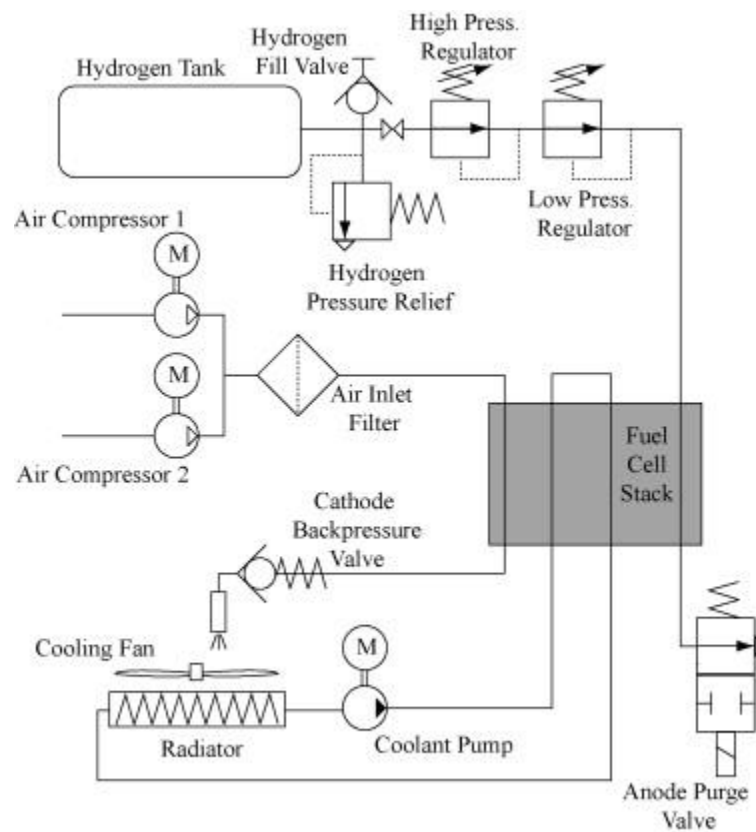


Figure 10. Fuel cell powerplant diagram and system specifications [14].

Under idle conditions, the output power of FC was only enough to produce the demanded power of UAV control and balance. A 1.26 Standard L min¹ of hydrogen produced 227W of a low heating value, whereas a waste of 168 W was measured from the anode discharge. The fuel cell produced 26 W of total electrical output (see Figure 11). During high power conditions, point 2, the fuel cell produced almost its maximum power (Figure 12). The fuel cell utilized more than 88% of hydrogen gas, and the low heating value (LHV) input of hydrogen was 1197 W. The fuel cell produced a total amount of 323 W out of its 465 W maximum power. The efficiency of the motor controller and electric power was 74 %, while the propeller efficiency was 70% which is low due to the low speed of aircraft. This causes a low propulsion efficiency of 14 %. Finally, for the cruising phase, as illustrated in Figure 13, the aircraft's propulsive power at Point 2 is 84 percent of its propulsive power at Point 1. The propeller efficiency was 80%, while the motor controller and the electrical motor achieved 66% efficiency. In comparison to a larger power situation, the electric motor's efficiency is reduced because it operates at a lower duty cycle, whereas the efficiency of the propeller is greater due to its operation at a larger advanced ratio. The whole propulsion system efficiency is 18%.

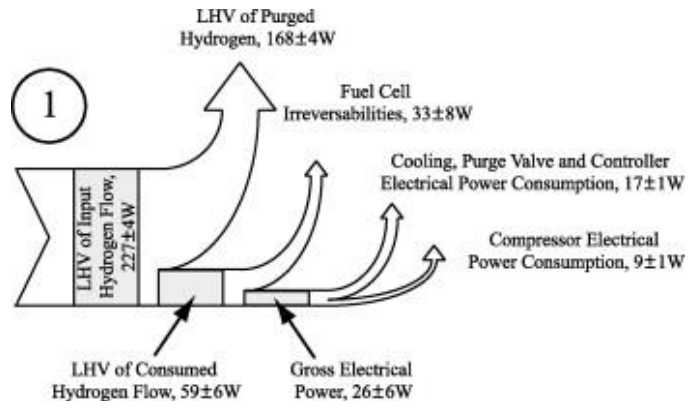


Figure 11. The losses at the idle case [14].

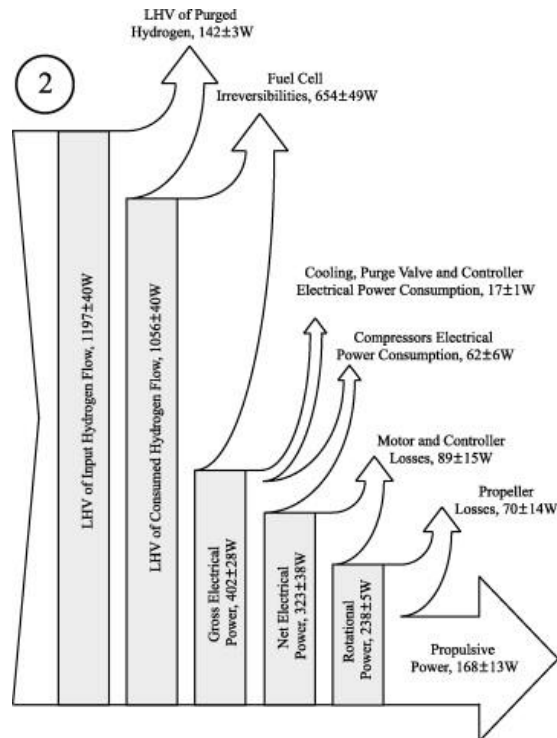


Figure 12. The losses at the high-power scenario [14].

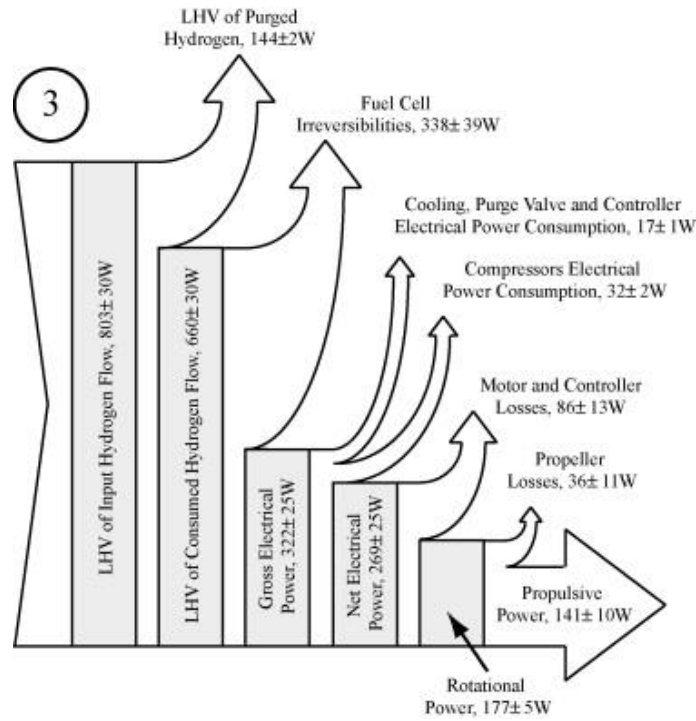


Figure 13. The losses at the cruise condition [14].

In a study [131] a fixed-wing UAV driven by a 100 W PEM was designed, demonstrating that a tiny FC with 100 W output could keep a UAV in level flight. Additionally, the study suggested that the PEMFC may be detached from the FC stack and connected in series beneath the UAV wing, eliminating the need to remove the stack's case and resulting in weight savings.

A new approach was investigated in ref [19] to evaluate and compare the endurance, the performance of an electric aircraft, power plant size, and the environmental impact of a UAV powered by a hydrogen fuel cell or lithium battery. There were two virtual powertrains examined (Figure 14). In all situations, the electric motor and propeller were the same. The losses and total efficiency of propulsion components are depicted in Figure 15. In the case of LiPo, the powertrain achieved an overall efficiency of 68 % at cruising and 48% at takeoff,

while the fuel cell powertrain system performed poorly, with 30.2% on cruise and 25.7 % at takeoff. The propeller suffers the greatest losses in a battery-based powertrain because of the other parts' high efficiency, whereas the fuel cell conversion losses are most essential in a fuel cell-based propulsion system. The study concluded that battery-powered powertrains are preferable for low-energy operations, while fuel cells are desirable for long-range operations.

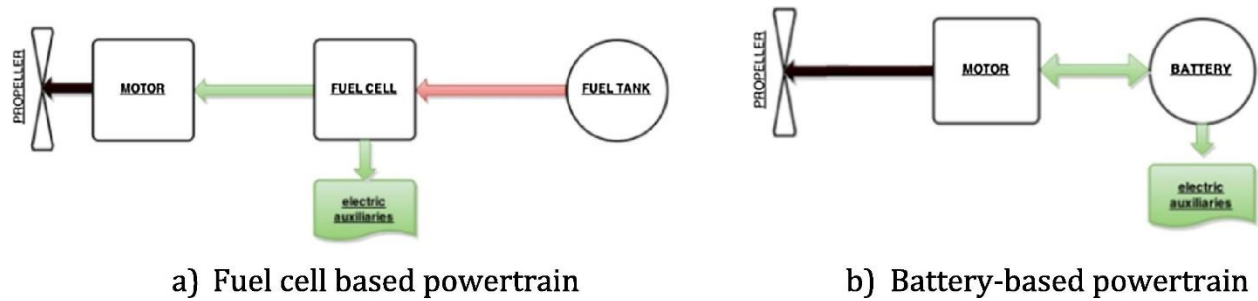


Figure 14. The proposed powertrains [19].

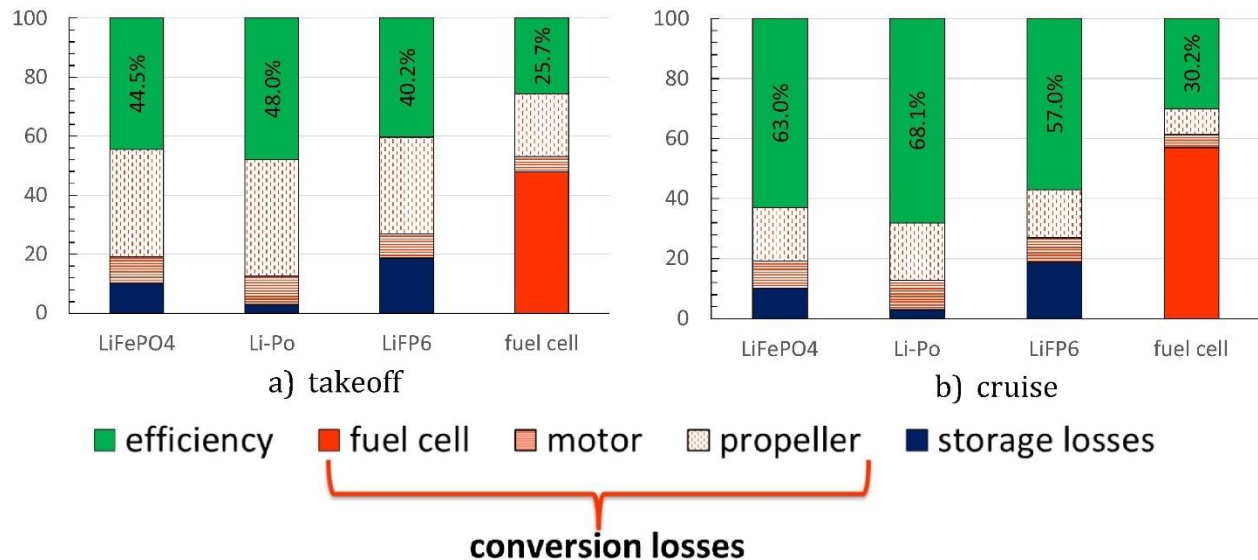


Figure 15. The energy balance introduced in the study model [19].

A numerical investigation was carried out in ref [132] using a 3-D, multiphase, and non-isothermal model on three different flow fields: unblocked bean-shaped, blocked bean-

shaped, and parallel (Figure 16). Figure 17 illustrates the schematic view of the air-cooled PEMFC in a proposed UAV. The governing equations of the computational fluid dynamic (CFD) for PEM fuel cells included mass, energy, momentum species, and charge equations. The numerical results were verified for the PEMFC model by comparing a polarization curve (Figure 18) of a single PEMFC to experimental results conducted by Mazumder et al. [133] and Heidary et al. [134]. The results of single-cell modeling were then applied to a polymer electrolyte membrane fuel cell (PEMFC) stack in order to generate 2.5 kW of power for an unmanned aerial vehicle (UAV). The findings showed that using rising air stoichiometry for cooling in an unobstructed bean-shaped design was effective, with the maximum temperature over the channel length reaching 331.5 K at an air stoichiometric ratio of 30. Additionally, the bean-shaped design without blockages had the best performance for a 2.5 kW PEMFC stack, with a volume power density of 1.1 kW/L and a mass power density of 0.2 kW/kg. It was also 9.4% lighter and 6.9% smaller than a parallel flow field design, making it a potential option for aviation use.

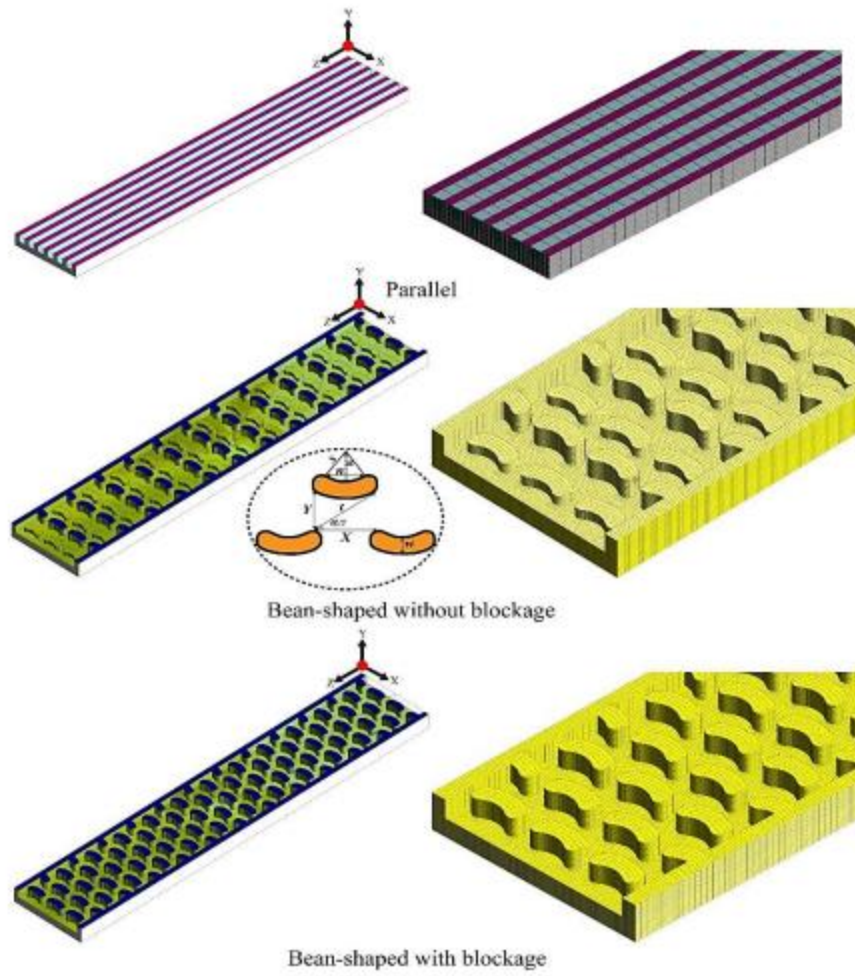


Figure 16. Geometry and mesh for the examined flow fields [132]

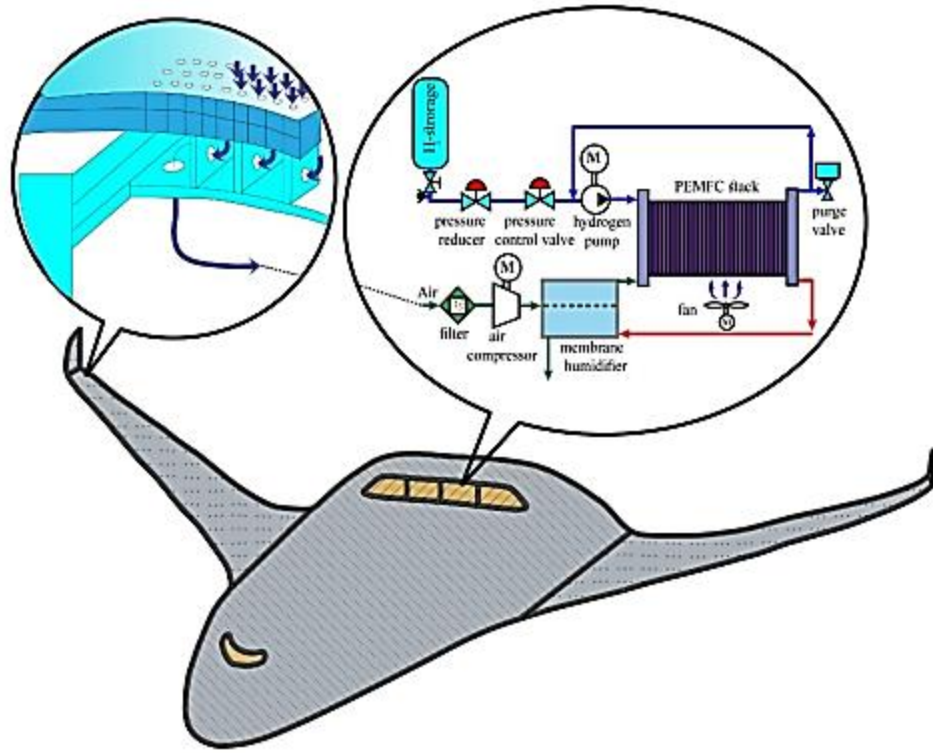


Figure 17. Schematic view of the air-cooled PEMFC in a UAV application [132]

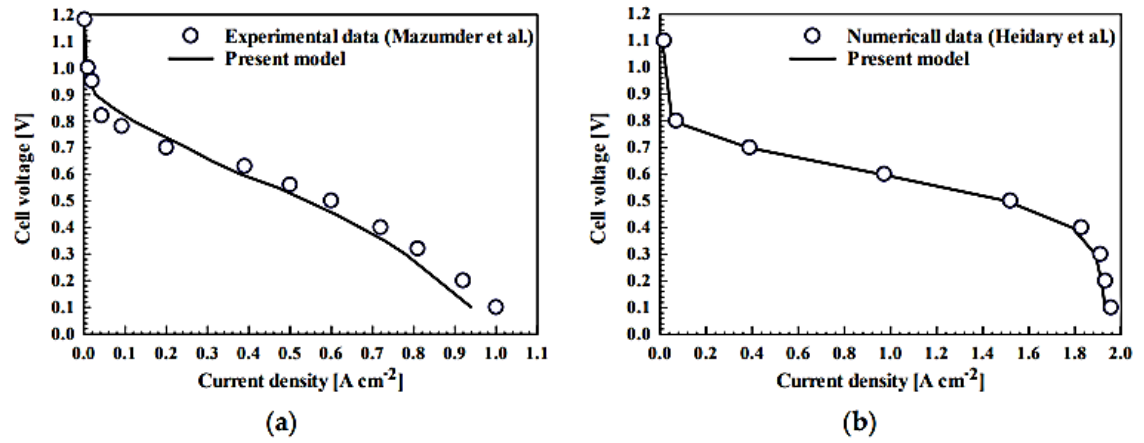


Figure 18. (a) Verifying of the numerical modeling with (a) experimental measurement of Mazumder et al. [133] and (b) numerical data of Heidary et al. [134] according to polarization curve.

2.7 UAVs Driven by Batteries

UAVs use many types of batteries, each with its own set of benefits and drawbacks. These types include Lithium Polymer (Li-Po), Lithium-Thionyl-chloride (Li-SOCl₂), Lead-acid (Pb-acid), Nickel Metal Hydride (NiMH), Nickel-cadmium (NiCad), Alkaline, Lithium-Ion (Li-ion), Zinc Oxide (Zn-O₂), and Lithium-air (Li-air). Li-Po and Li-Ion types are the most common batteries used for UAVs. The best type of battery is chosen by considering the power density, energy density, weight, volume, lifetimes, affordability, reliability, and maintenance of the many possibilities [2]. Each of these parameters has an impact on distinct parts of the UAV: power density influences acceleration, energy density promotes range, lifetime influences how frequently the battery must be changed, weight and volume influence overall range, and cost influences availability [2,135]. Table 2 summarizes several specifications for various battery types.

Lead-acid batteries are the most widely utilized type in UAVs due to their inexpensive cost and high power-to-weight ratio. The output power might be non-linear, and the lifespan is heavily influenced by the load profile. Lead-acid batteries have a unique disadvantage over other battery technologies in that they have a lower energy density, resulting in a shorter lifespan. As a result, they're increasingly being used as a backup power source [136]. Li-ion batteries have a high power and energy density per unit of battery mass, and they are smaller and lighter than conventional rechargeable batteries. In addition, Li-Ions have low energy consumption and a relatively long lifetime. This type has the disadvantage of high cost [137]. In general, the major benefits of UA batteries are that they can be charged practically anywhere, moved almost anywhere, and quickly refilled by just changing the battery pack.

The drawbacks include a limited number of recharge cycles and relatively low energy densities.

Most small UAVs have battery-based propulsion systems, especially those quadrotor drones. In fact, batteries are considered the prime power source in these UAVs [138,139]. This usage of batteries enhances the propulsion system's flexibility and simplicity. Furthermore, based-batteries UAVs have various applications in daily life in terms of time and cost-effectiveness. However, the endurance of small battery-based UAVs is short due to battery pack weight. Typically, they can fly for a maximum of 90 minutes using Li-Po batteries [140]. Li-Po batteries are preferred for small UAVs because of their relatively high specific energy and low weight. In fact, the Li-Po batteries powered 90 % of micro-UAVs less weighted than 2 kg [141].

Table 2. Different battery specifications [2,135,142–145].

Battery type	Power density (W/kg)	Energy density (wh/kg)	Nominal voltage density (V)	cycle life
Li-po	120-200	30-40	2.7-3	200-300
Li-ion	1000-1500	100-150	3.6–3.85	500-1000
Li-air	11 -400	11- 140	2.91	700

Pb-acid	120	30-40	2.1	less than 350
Alkaline	50	85-190	1.3-1.5	N/A
Zn-O ₂	442	100	1.45-1.65	100
NiCad	150	40-60	1.2	2000
Li-SOCl ₂	18	500-700	3.5	NA
NiMH	250-1000	50-80	1.2	300-500

Recently, electrical propulsion systems have gained significant attention among small and mini-UAVs. Tremendous efforts have been devoted to electric UAV's power estimation and optimization [18,146]. Chang and Yu [16] studied the impact factors that affect the UAV flight endurance, such as the battery damping system weight ratio. The study compared and optimized the endurance of a fixed-wing UAV utilizing the genetic algorithm (GA). The results revealed that increasing the battery weight ratio is not necessarily improving the UAV endurance. On the other hand, however, the increase in the weight ratio of the battery damping system can significantly improve endurance. Mathematical relations were used to evaluate the flight range and endurance of based-battery aircraft in ref [146]. They examined the influence of the voltage discharge and battery discharge rates on the effective capacity. It has been shown that the so-called Peukert effect improves aircraft endurance and range when battery capacity is larger due to the required current. However, the effective capacity

decreased when the current draw was close to the battery's nominal capacity. The battery capacity effect and voltage discharge on the aircraft endurance and range is illustrated in Figure 19 & Figure 20. Recently, a study [147] has shown that the effective capacity of Li-ion batteries is almost independent of their voltage discharge rate. An experimental investigation has been carried out to show and validate the endurance of battery-based model aircraft in ref [148]. Various li-Ion batteries were utilized to power the aircraft model. The study recorded the characteristics of batteries. Based on these characteristics, a theoretical flight endurance estimates within 3 % of what was experimentally measured.

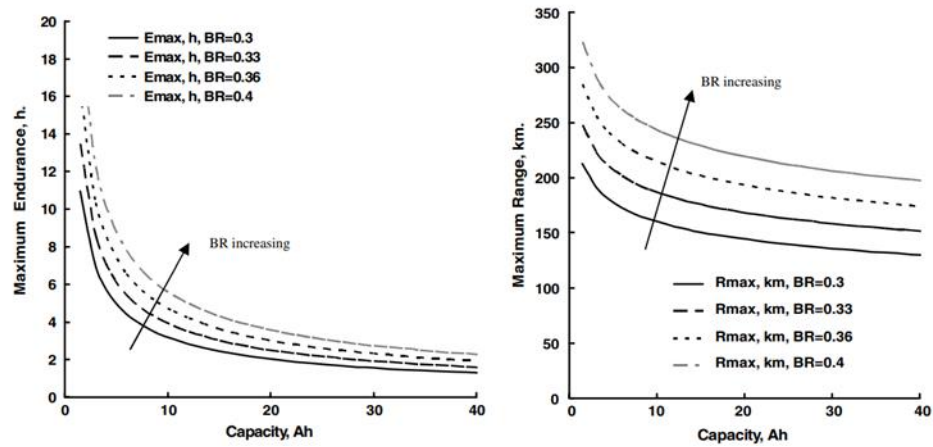


Figure 19. The battery capacity vs flight range and endurance [146].

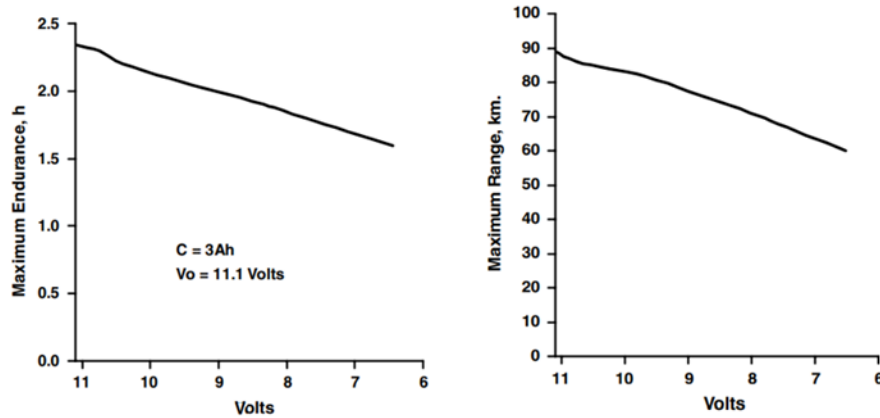


Figure 20. The effect of battery voltage discharge on the aircraft endurance and range [146].

2.8 UAVs Driven by Solar Cells

The use of photovoltaic panels as UAV's primary power source is considerably increasing. The solar cells installed into the UAVs wing will supply endless power for the UAV battery during the day or night flights. Because photovoltaic panels can only produce energy during the daytime, all PVs must have a storage component, usually a battery [149]. Typically, batteries are classified as either primary or secondary types. The primary types are those which cannot be recharged, and the secondary are those rechargeable types. For solar aircraft, secondary batteries are used as energy storage [150]. Fuel cells are also another method of energy storage that can be utilized in solar-based aircraft.

Abbe and Smith [150] reviewed the technological trend and developments in solar-power aircraft. They discussed the design issues of solar aircraft, including the issues of propulsion systems, structures, aerodynamics, etc. Additionally, technological status and trends related to PVs system, power management systems, and energy storage have been discussed in detail. In general, solar cells are developed and designed for HALE UAVs applications

(Figure 21) because HALE UAVs are designed to fly at very high altitudes and long continuous missions. Romero et al.[151] Presented a mathematical model for a UAV powered by solar energy. The study analyzed the performance of UAV longitudinal control, applying successive loop closure. Additionally, a PV array reconfiguration methodology was investigated to allow the load to deliver maximum power. They concluded that the PV array could handle the aircraft's demanded energy.

Harvey et al. [152] developed a power system model to study the potential performance of hybrid electric UAVs. Solar cells were introduced into the model and resulted in significant power improvement. For surveillance missions, The SCs provided 59 % of energy savings despite the increase in the UAV weight. Morton et al. [20] designed a small prototype UAV driven by solar panels and validated it through several experimental tests. The experimental results revealed that the quantity of solar energy received is sufficient for the UAV to carry more payload and extend the flight endurance.

The main objective of photovoltaic HALE UAVs is to fly at high altitudes for long periods of time. As a result, in addition to waiting for significant technological advancements in ultra-lightweight structures or lithium-sulfur batteries, it is critical to carry out studies into alternate methods for increasing flying durability. Several studies have been investigating the importance of power management systems (PMS) in order to achieve optimal efficiency and power for solar-power aircraft. For instance, a solar power management system (SPMS) was designed and introduced in ref [149]. The SPMS consisted of battery management, maximum power point tracking MPPT, and power conversion stages. Since SCs-UAVs require a large wingspan to optimize the quantity of sun's energy gathered, a

maximum power point tracking (MPPT) technique is necessary in this case [153]. In this case, the MPPT hardware system consists of a basic converter, a low-cost microcontroller, as well as current and voltage sensors. The MPPT phase tries to extract as much energy as possible from the PV arrays. The Li-ion polymer battery modules' charge and discharge operations are monitored and controlled by the battery management stage. The final step is power conversion, which includes dc/dc synchronous buck converters that create +5 V and +12 V for onboard computers and other electronic circuits. Pen et al.[153] developed an innovative perturb and observed-based MPPT algorithm for achieving the best SC performance under quick multi-changing solar irradiances, which might be the case for UAVs.



Figure 21. Solar-Powered HALE UAV [154]

Gao et al. [155] proposed an EMS for HALE UAV based on the idea that the PV power can be partially stored in the daytime in gravitational potential. The results showed that, with the proposed EMS, the UAV could maintain above 16 km of altitude. Additionally, the proposed

EMS was able to reduce the amount of power consumed by the airplane during night flights. As indicated in Figure 22& Figure 23, when compared to the present EMS, the suggested EMS leaves roughly 23.5 percent of energy in the batteries after one day-night cycle, which indicates that about 23.5 percent of the weight in the battery may be removed. The same EMS based on gravitational potential were simulated in [156]. The study provided some basic principles for solar HALE to obtain optimal flight endurance with minimal or zero rechargeable battery. It can be concluded that the efficiency and flight time of solar UAV are significantly enhanced by the EMS that uses gravitational potential.

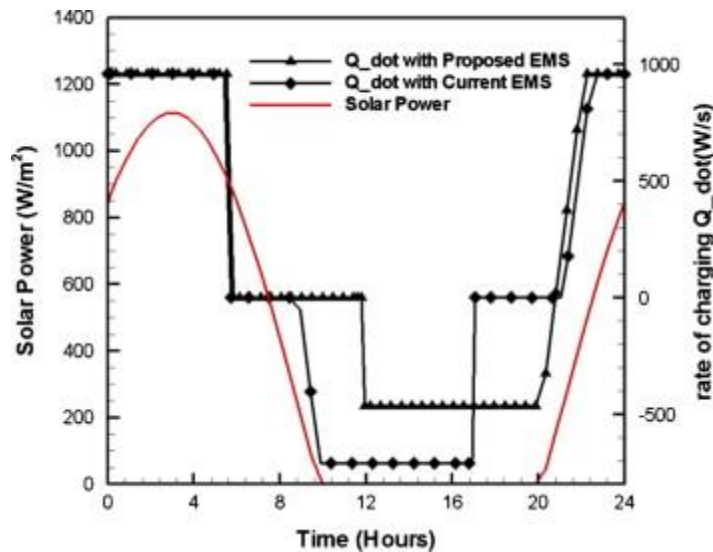


Figure 22. The charging rate compare [155].

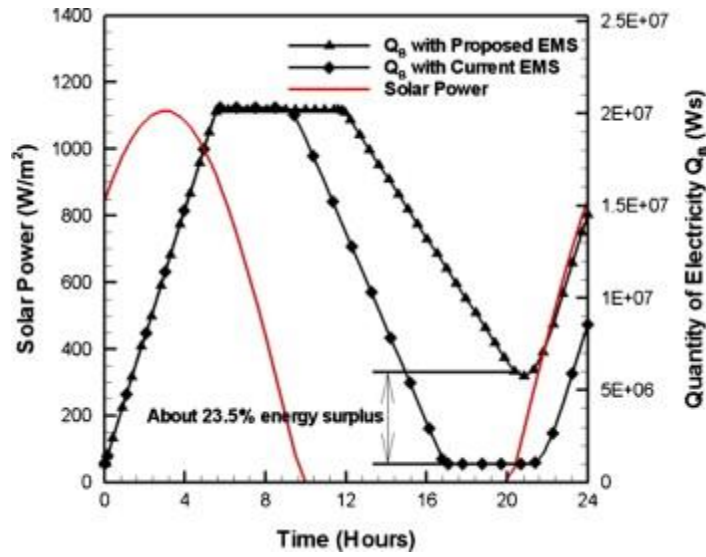


Figure 23. The amount of electricity compares [155].

2.9 UAVs Driven by Hybrid Power Sources

Hybrid power systems are systems that integrate several power sources. By using more than one power source on aircraft propulsion and components, hybrid systems can extend the flying duration and reduce pollutants [141,142]. Hybridization can also minimize the system's capital cost, reduce its bulk and volume, and increase its efficiency [110,143]. Hybrid systems, on the other hand, comprise dynamic subsystems and passive or active power-management systems, which provide design and implementation issues that must be considered when integrating into the entire vehicle [144,145].

2.10 Hybrid FC with Battery

Hybrid systems based on FC/batteries are the most common and feasible option for powering UAVs, primarily to improve their effective range. The Hawaii Natural Energy Institute [157] was the first to suggest a partial-hybrid architecture that combined the fuel cell with the

battery. The institution confirmed the potential advantages of fuel cell/battery and converter hybrid types through their partnership with the US Navy's Naval Research Laboratory. Cranfield University created and investigated a hybrid propulsion system by connecting the fuel cells in parallel with the battery and DC/DC converter in two similar works. The results showed improvement in rapid power requirement and UAV endurance [158,159]. In order to use integrated energy sources like fuel cells combined with a battery in a hybrid system manner, a powertrain design is required. Researchers have created many powertrain architectures. Gonzales et al. [160], for instance, employed a simple energy management technique to determine the energy requirements of an autonomous ground vehicle powered by 200W PEMFC integrated in parallel with 6 Li-Po cells with no charge constraint.

Limited studies of static and dynamic behavior and performance of hybrid FC/battery systems for UAVs are reported in the open literature[8,17,161]. However, a number of experimental studies [17,162–164] investigated the characteristics of small UAVs' hybrid power systems. The studies show the battery's role in hybrid systems using a commercial Aero-Stack fuel cell + battery system. A 200-W proton-exchange membrane (PEM) fuel cell, its controller, a 6S lithium polymer (LiPo) battery, and a power-management board make up the Aero Stack hybrid system. To address the high-power needs during UAV take-off or ascending, the 6-cell ThunderPower 1350-mAh 25C lithium polymer (LiPo) battery pack can offer an extra 400 W for 2 minutes. The LiPo battery is also essential for responding quickly to load changes and avoiding fuel-cell starvation.

Three types of batteries (Li-ion, Ni-Cd, and Ni-Mh) integrated with fuel cell systems have been studied based on comparing power and energy densities, temperature effects,

endurance, efficiency, and discharging performance in refs [19,165]. However, they did not conduct flight tests in order to study the behavior of power and energy performances under different flight conditions.

Generally, hybrid power systems are classified into active and passive architectures. The active configuration has a DC/DC converter used for operating conditions and decoupling size of the FC/battery hybrid system. the passive configuration, on the other hand, has a direct coupling among the system elements [160]. The passive architecture has different possible configurations depending on whether the FC can charge the battery without any limitation (Figure 24 a), with limitations and regulations process (Figure 24 b), or impossible for the fuel cell to charge the battery (Figure 24 c) [160]. Several studies and projects have investigated passive and active hybrid systems for UAVs [35,161,165,166]. The passive configuration is mostly applied for a hybrid power system of a small unmanned aerial vehicle, usually the architecture shown in Figure 24b [160].

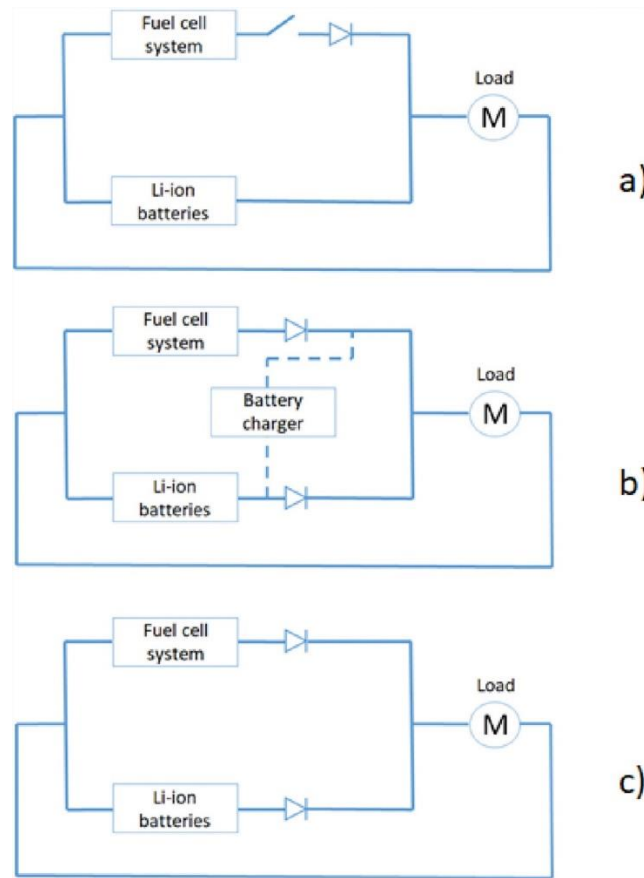


Figure 24. Passive configuration of FC/Battery hybrid power system [160].

A combination of PEMFC – Li-Po battery system was constructed in [167] by comparing three architectural models and using a mini battery-only UAV shown in Figure 25 for testing. The first scenario applied when the FC deliver 330 W in an instant with the battery covering the remainder as illustrated in Figure 26. In the second case, the power output delivered by the fuel cell was increased, and the remaining was covered by the battery as shown in Figure 27. The third scenario is constructed using a low-density battery that will only meet the needed power in short circuits rather than the 7S Li-Po battery required for the fuel cell humidification method (Figure 28). Modeling and testing processes were carried out with the use of experimental power demand data from a fixed-wing UAV. During the ground test,

the variation of the fuel cell and battery voltage was analyzed. The results revealed that the fuel cell was shown to meet around 160–170 W of the 250 W power (Figure 29).



Figure 25. Testbed UAV platform[167].

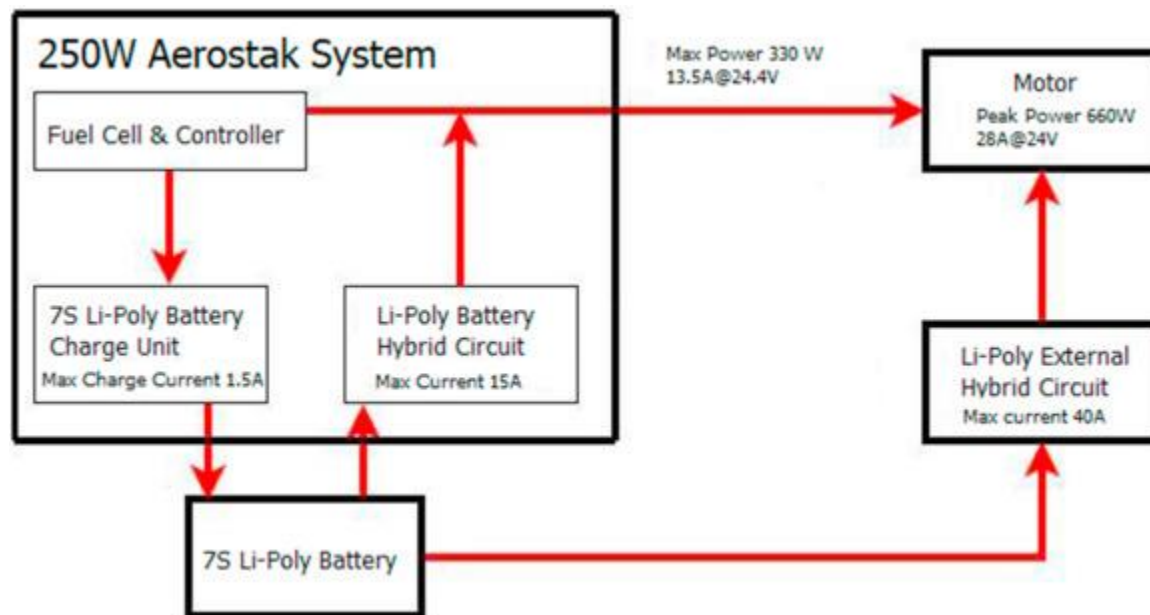


Figure 26. Configuration of Scenario 1 hybrid system [167]

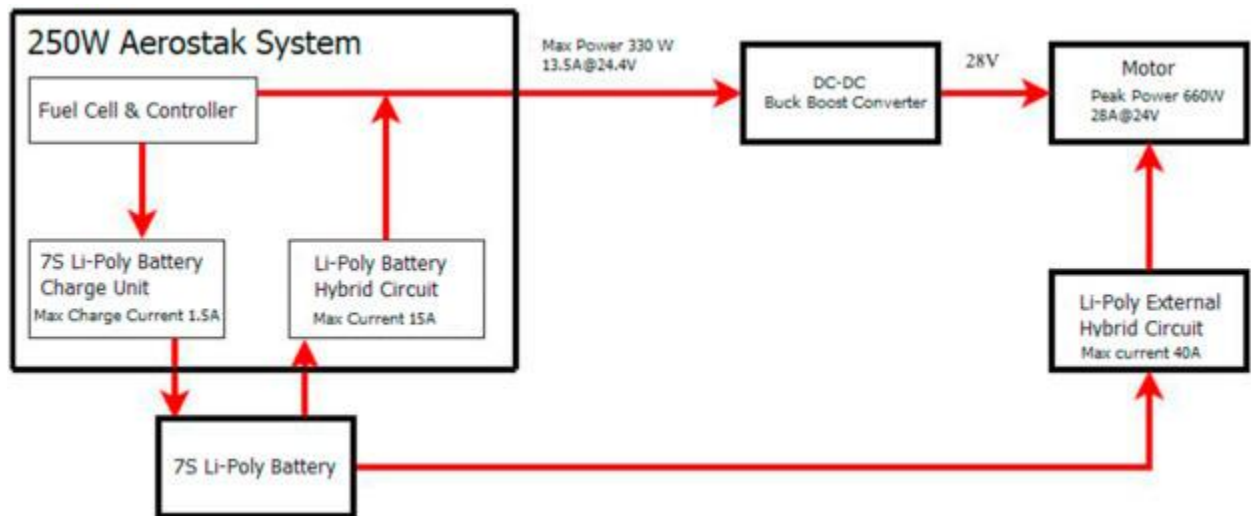


Figure 27. Configuration of Scenario 2 hybrid system [167].

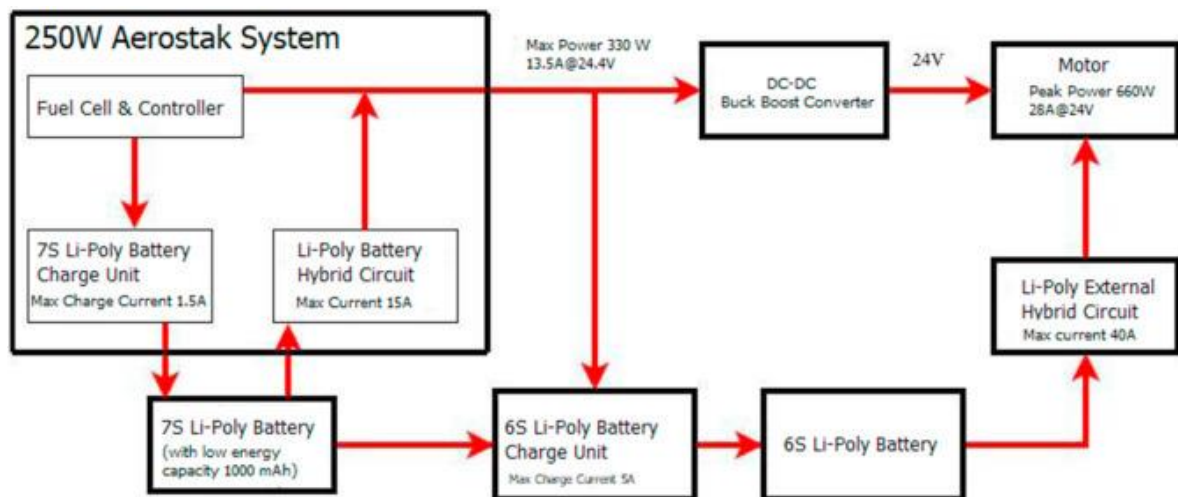


Figure 28. Configuration of Scenario 3 hybrid system [167]

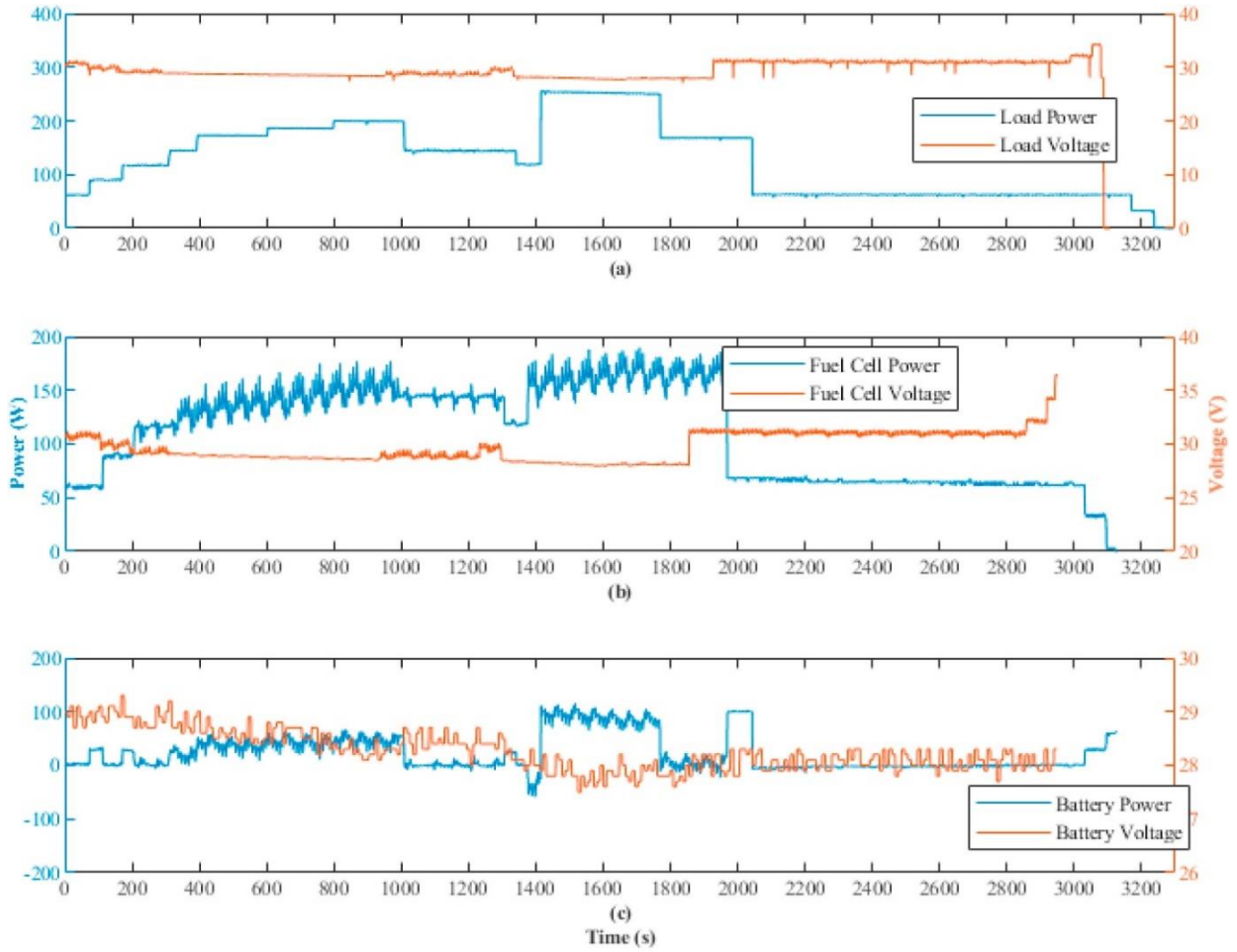


Figure 29. (a) The load's time dependent power/voltage, (b) fuel cell's time-dependent power/voltage, (c) battery's Time-dependent power/voltage [167].

John T et al. [168] described the power and density management system of hybrid PEM fuel cell and a Li-Ion battery integrated into UAVs. The hybrid system was modeled and simulated by MATLAB software. The nominal power of the PEM was 1.2 kW, and the maximum power output was 2 kW. The Li-Ion nominal voltage was 24V and the battery's initial charge was 50%. The results revealed that the voltage of the fuel cell system was increased after the FC motor operated at optimum motor voltage.

A comparison study of Li-Ion, H₂ fueled combustion engine, and fuel cell deriving a small UAV has been simulated and modeled in ref [169]. The study focused on modeling Raven RQ-11B UAV using five powertrain options; Li-Ion and Li-Po battery, internal combustion engine (ICE) generator, parallel hybrid ICE, PEMFC, and Free Piston Engine (FPE) integrated with a linear generator. The flight conditions were at level flight with constant velocity. When evaluating the depth of discharge estimations to experimental results, two models conducted in refs [170,171] was used to represent lithium-ion batteries, and the findings showed excellent accuracy. Because PEMFCs have a lower power density than internal combustion, this option will necessitate a bigger hydrogen tank and more compact design. The PEMFC, like the FPE, has the benefit of being able to give power directly without the need for a complicated system, and it looks to be capable of delivering the needed specific power. Moreover, using a lithium-air battery would provide the greatest flying endurance and be the most straightforward to set up. Finally, Figure 30 depicts the anticipated best-case flying time scenario for each powertrain choice.

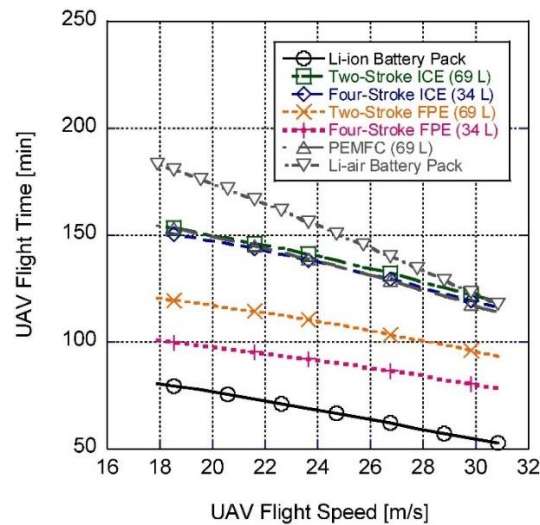


Figure 30. Comparisons of best-case scenario UAV endurance[169].

Modeling is critical element in the design of hybridized power systems that employ PEMFCs and other power supplies for UAVs propulsion systems, which have varied power demands throughout flight stages [172–174]. The survey has chosen studies including hybrid power systems and UAVs demonstration. The data from the survey is shown in Table 3.

Table 3. studies of UAVs powered by hybrid systems.

Fuel cell type	battery type	study approach	reference
PEM 150 W	Li-Po	Design	[175]
PEM 500 W	Li-Po	Simulation/experimental	[176]
EOS 600 PEM	Li-Po Battery	Experimental	[177]
Concept PEM	Li-Ion	Modeling and simulation	[178]
PEM 150W	Li-Po and Supercapacitor	Simulation	[179]
PEM 250 W	Li-Po Battery	Design and experiment	[161]

PEM 200W	Li-Ion/Ni-Mh Battery	Modeling and simulation	[180]
PEM 250 W	Li-Po battery	Modeling/simulation and experiment	[167]
PEM	Li-Ion battery	Modeling	[168]
PEM 200 W	6S Li-Po battery	Experiments using The Aero Stack hybrid system	[17,162– 164]

2.11 Hybrid FC with Solar Cells

Fuel cell systems can be combined with photovoltaic solar panels system to supply continuous, high-quality electricity for the flight's extended-duration missions [181]. Limited studies have been carried out to investigate the performance of UAVs powered by a combination of fuel cells and solar power. This integration has been tested to show an improvement in flight efficiency and power [174]. Utilizing this technique helps maintain overall efficiency [182] and can enhance endurance by up to 22 % for small UAVs [183].

Zafar and Gadalla [173,183] evaluated and analyzed integrated hybrid FC/PV power systems for a small UAV model. The results indicated that the endurance of UAV integrated with FC/PV increased by 100% as compared to only-fuel cell power system. This increase in endurance could result in a longer range and hence lower operational cost.

Maintaining equivalent flying capabilities to the battery system necessitates carrying large fuel loads in the fuel cells [184]. Similarly, relying solely on batteries may result in insufficient UAV endurance [185] that are unsuitable for long-haul missions. Furthermore, batteries must be recharged before a flight, and this can be a time-consuming procedure as compared to filling a hydrogen tank [186]. Given that PVs power is restricted to sunlight [187], the integration of photovoltaic and batteries allows UAVs to fly continuously during the day and night [5,188]. As a result, UAVs driven by a hybrid combined PVs and batteries energy are more cost-effective and practical than aircraft powered by fuel cells and solar panels [189]. Such studies confirm the importance of developing solar-based electrical UAVs.

2.12 Hybrid FC, Battery, and Solar Cells

For the fully renewable hybrid power source UAVs, most studies in open literature only considered FC/battery [175,176,190] hybrid systems or battery/solar cells [150,155,156,191]. Very few studies investigated the FC/battery/ solar cell power system [192–196] because of their complicated system. When compared to a single fuel cell propulsion system, an FC/Battery/Solar cell hybrid power system might accomplish roughly double the flying duration in a small UAV [173]. Gang et al. [21] implemented a hybrid power system of a 300 W PEMFC connected with a battery and an 80 W solar cell system with a battery to UAV model shown in Figure 31. The study tested the flight for long endurance UAV according to the mission flight depicted in Figure 32. The fuel cell system is composed of a NaBH₄-based hydrogen generator, PEMFC of 300 W, and a microprocessor controller, as shown in Figure 33. The solar cell system was composed of four 80 W SCs module and a lithium polymer battery (Figure 34).

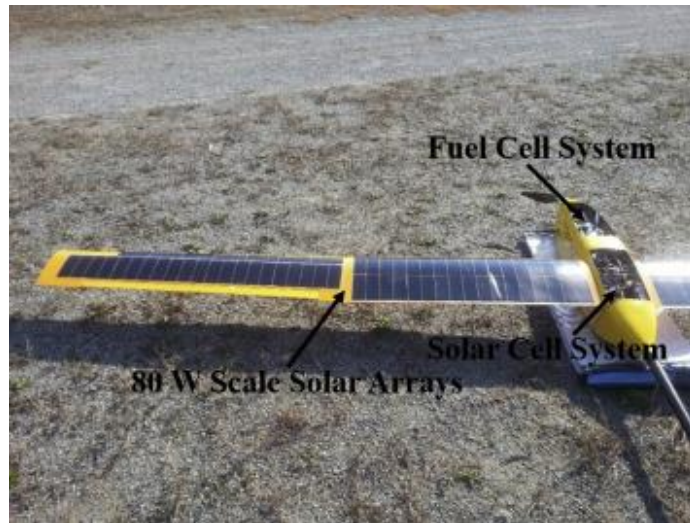


Figure 31. The UAV with FC and SC system [21].

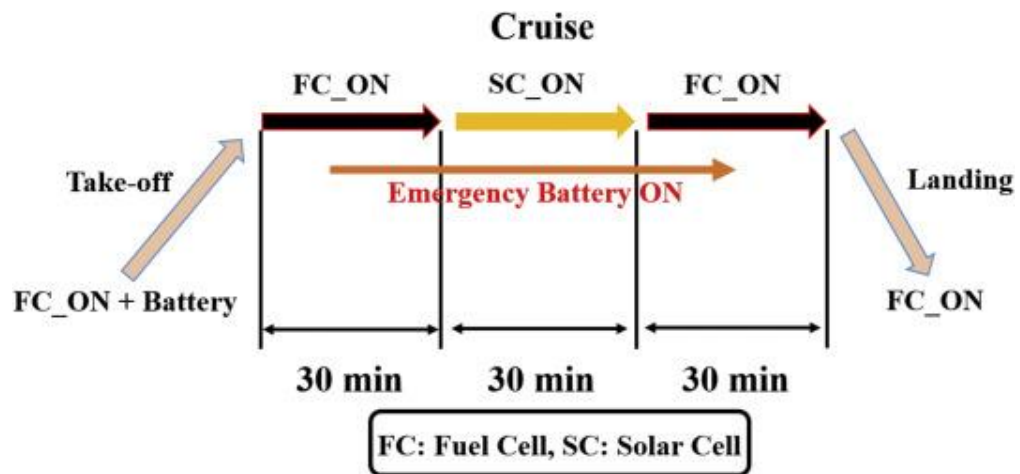


Figure 32. Flight mission profile using hybrid system FC/battery/SC [21].

A 1.5-hour flight test examined the proposed hybrid propulsion system by transitioning from FC to SC power and vice versa, showing system robustness and increasing UAV endurance.

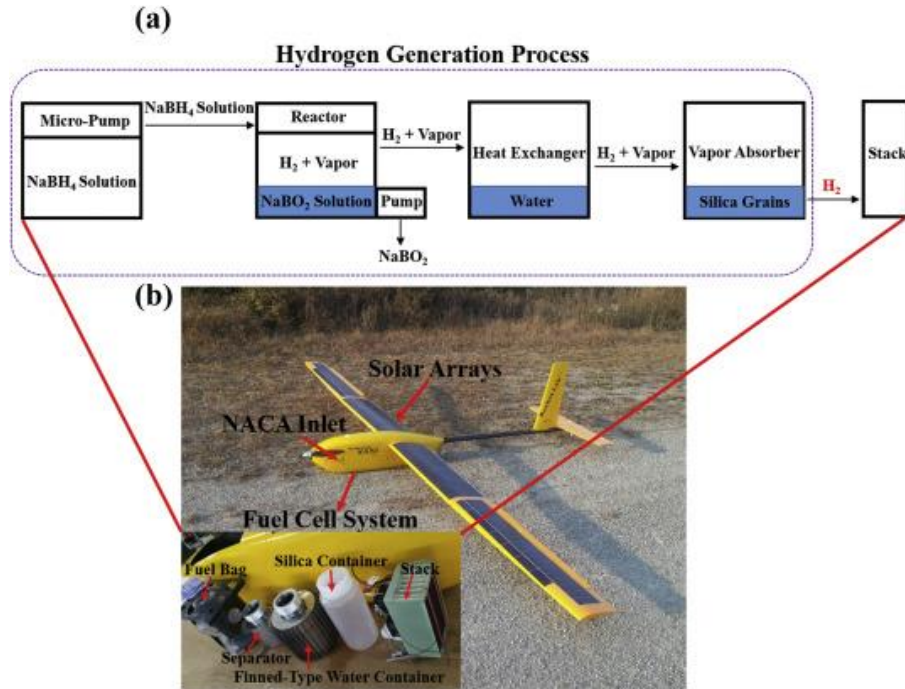


Figure 33. FC system: (a) hydrogen generator process (b) FC installed system [21].

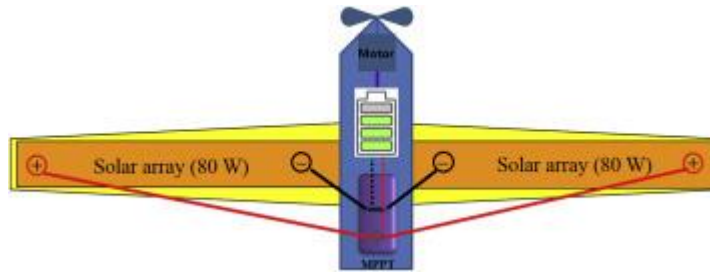


Figure 34. Solar cell powered- UAV model [21].

Lee et al. [174,196,197] investigated and tested the power management system and flight test of a mid-class UAV (EAV-2) using a hybrid electrical power system consisting of fuel cell + battery + solar cells (Figure 35). The flight test was conducted for 22.13 hours after take-off. A mathematical model was used to analyze the dynamic behavior of fuel cells, batteries, and solar cells. The solar cells were used as a primary power source during day flight, while the fuel cell acted as the primary power source during night flight. Additionally, their studies

applied an active and passive power management system. Both power management methods were simulated and compared for 4.5 hours. The simulation results revealed that the active management could maintain a minimum state of charge (SOC) for the battery, which leads to an increase the power distribution efficiency and greater system safety. For the passive management system, where no DC-DC controller was implemented, the three-power source would operate with the same operational voltage. As a result, using a supercapacitor with photovoltaic cells in a passive architecture would be ineffective [198].

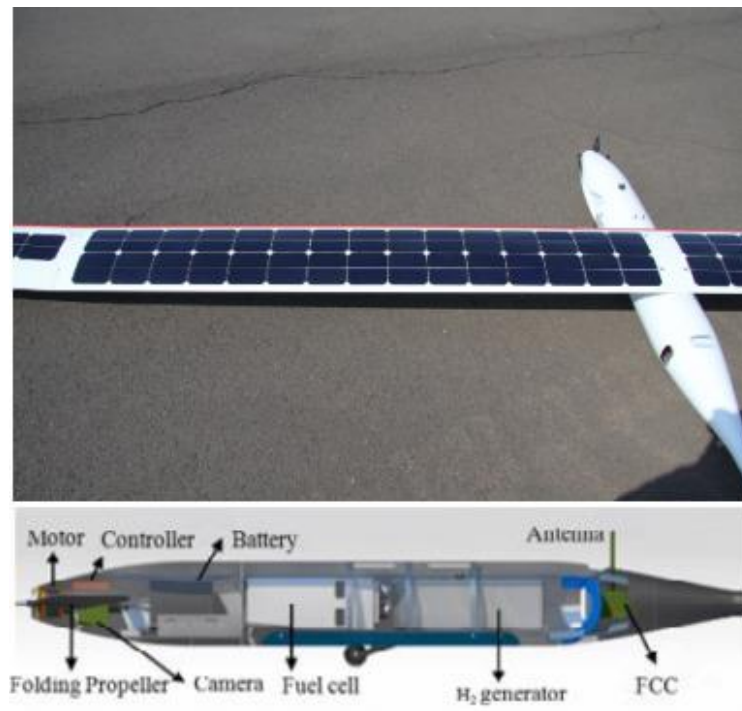


Figure 35. Solar cells in the wing, and the EAV-2 system configuration [174,196,197].

Zhang et al [194] proposed hybrid power system with a combination of PEMFC/ Li-Ion battery/ photovoltaic panels to increase the flight time of a low altitude UAV. The proposed study used energy management strategy (EMS) to analysis the power of the three power sources. The hybrid system provided energy for the BLDC motor and avionic components

through an energy management controller. The configuration of a hybrid system used is depicted in Figure 36. Because of the large power demand from taxi out to cruise conditions, the Li-Ion battery is responsible for the power demand (Figure 37 a). The power output of solar cells, batteries, and fuel cells are represented in Figure 37 b, Figure 37 c, and Figure 37 d, respectively. According to the suggested EMS, the output power of the battery fluctuated significantly, while the FC worked almost at its highest efficiency.

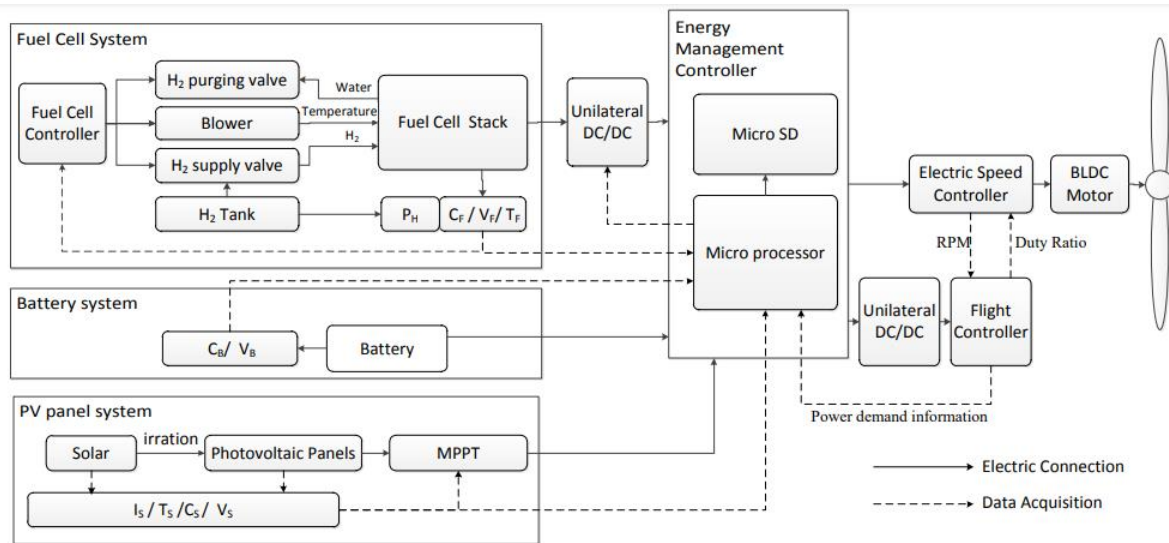


Figure 36. Schematic of hybrid propulsion system [194].

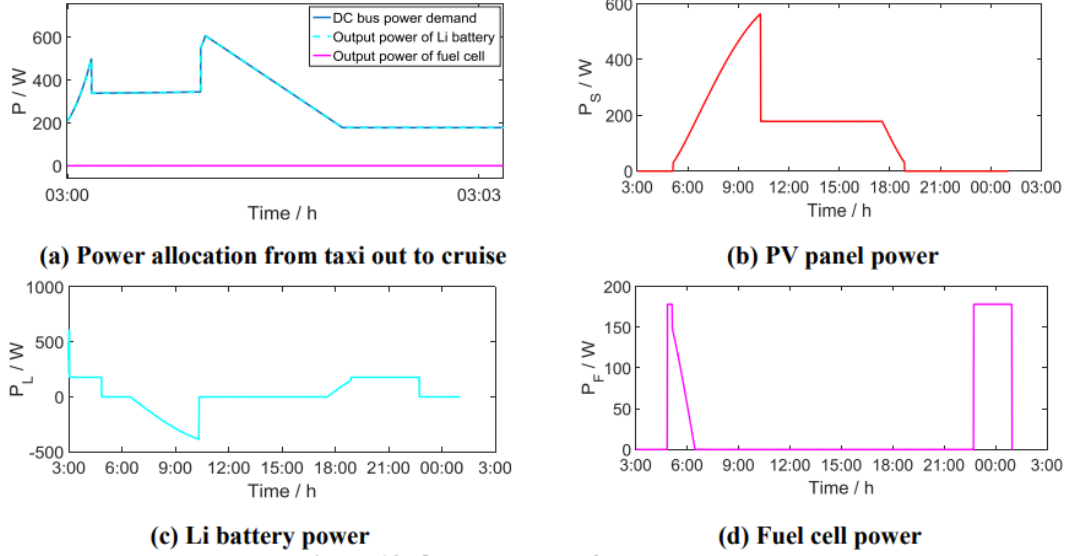


Figure 37. Output power for each system source [194].

Most optimization studies considered the PEM fuel cell model to find the most optimal voltage and efficiency output and compare them to the experimental values provided by the manufacturer data. However, there are big gaps in the literature regarding implementing PEM fuel cells into the UAV propulsion system in order to optimize the UAV performance accordingly. So, in this study, these optimized models will be integrated with the UAV propulsion system to get the optimal performance based on different optimization algorithms. Also, only a few investigations studied the hybrid system integrated into the UAVs, especially the full setup of fuel cell /battery/ solar cell.

CHAPTER 3 MODELING AND FORMULATION

In this section, modeling, and formulation of the three models have been introduced. A mathematical model for fuel cells has been proposed for a PEM fuel cell. The fuel cell model then integrated into UAV, which has a mathematical model for evaluating performance. Additionally, a rotary coaxial drone has been modeled and introduced, this model uses Li-Po battery as a power source. Moreover, this section proposed a PV mathematical model and then integrated PV model and battery with a UAV. After proposing these mathematical models and formulations, each model is evaluated and discussed in the result and discussion section.

3.1 Fuel Cell Model

PEMFC output voltage is formulated from refs [55,199] as:

$$V_o = N_{nc}(E_{oc} - E_{op} - E_o - E_{ops}) \quad (15)$$

where, N_{nc} is the number of PEM cells connected in series, E_{oc} is the open circuit potential condition per cell, E_{op} is the activation over-potential of the cells, E_o describes the Ohmic voltage drop in each cell and E_{ops} is the over-potential saturation in cells.

Nernst equation has been utilized in ref [200,201] as:

$$\begin{aligned} E_{oc} = & 1.23 - 8.5 \times 10^{-4}(T_{PEM} - 298.15) \\ & + 4.31 \times 10^{-5} \times T_{PEM} \times \ln \left(P_{H_2} \sqrt{P_{O_2}} \right) \end{aligned} \quad (16)$$

Where T_{PEM} represents the fuel cell operation temperature (K). P_{O_2} and P_{H_2} are the partial pressures of oxygen and hydrogen, respectively, and they can be evaluated by [202]:

$$P_{O_2} = R_{hc} \times P_{H_2O} \left[\frac{1}{\frac{R_{hc} \times P_{H_2O}}{P_c} \times e^{\frac{1.635 I_{PEM}/A}{T^{1.334} I_{PEM}}} - 1} \right] \quad (17)$$

$$P_{H_2} = \frac{R_{ha} \times P_{H_2O}}{2} \left[\frac{1}{\frac{R_{ha} \times P_{H_2O}}{P_a} \times e^{\frac{1.635 I_{PEM}/A}{T^{1.334} I_{PEM}}} - 1} \right] \quad (18)$$

where R_{hc} , P_a , and P_c are relative humidity vapor electrodes, anode, and cathode inlet pressures, respectively. I_{PEM} is the fuel cell current (amps). The saturation pressure of the water vapor P_{H_2O} is estimated by the following expression [203]

$$\log_{10}(P_{H_2O}) = 2.95 \times 10^{-2} T_c - 9.18 \times 10^{-5} T_c^2 + 1.4 \times 10^{-7} T_c^3 - 2.18 \quad (19)$$

where the T_c can be expressed as:

$$T_c = T_{PEM} - 273.15 \quad (20)$$

The activation over-potential is formulated as:

$$E_{op} = -[\xi_1 + \xi_2 T_{PEM} + \xi_3 T_{PEM} \ln(C_{O_2}) + \xi_4 T_{PEM} \ln(I_{PEM})] \quad (21)$$

$$\xi_2 = 2.9 \times 10^{-3} + 2.1 \times 10^{-4} \ln(A) + 4.3 \times 10^{-5} \ln(C_{H_2}) \quad (22)$$

Where $\xi_{1,2,3,4}$ are semi-empirical coefficients of each cell model. C_{O_2} and C_{H_2} are the oxygen and hydrogen concentrations in the cathode catalyst interface (mol/cm³), respectively, which can be evaluated as [60].

$$C_{O_2} = \frac{P_{O_2}}{5.1 \times 10^6} \times e^{\frac{498}{T_{PEM}}} \quad (23)$$

$$C_{H_2} = \frac{P_{H_2}}{1.1 \times 10^6} \times e^{\frac{-77}{T_{PEM}}} \quad (24)$$

The cell ohmic voltage is expressed as:

$$E_O = I_{PEM}(R_m + R_c) \quad (25)$$

where R_m , and R_c are the equivalent resistance of the membrane and the resistance to the transfer of protons through the membrane, which is usually considered constant [204]. The expression of R_m is:

$$R_m = \rho_m l S^{-1} \quad (26)$$

where ρ_m , l , and S are the Nafion membrane resistivity for the electron flow ($\Omega \cdot \text{cm}$), membrane thickness (cm), and the cell active area (cm²), respectively. The Nafion membrane resistivity is introduced in [204] as:

$$\rho_m = \frac{181.6 \left[0.062 \left(\frac{T_{PEM}}{303} \right)^2 \left(\frac{I_{PEM}}{S} \right)^{2.5} + 0.03 \left(\frac{I_{PEM}}{S} \right) + 1 \right]}{\left[\lambda - 0.063 - 3 \left(\frac{I_{PEM}}{S} \right) \right] \times e^{\frac{T_{PEM}-303}{T_{PEM}}}} \quad (27)$$

where λ is a parameter coefficient related to the membrane preparation procedure [201]. The cell over-potential saturation due to the mass transport is calculated as [55]:

$$E_{ops} = -\beta \ln \left(1 - \frac{J}{J_{max}} \right) \quad (28)$$

where β is a parametric coefficient (V), J is the actual cell current density (A/cm²) and J_{max} is the maximum of J .

The output fuel cell power can be evaluated as:

$$P_{fc} = I_{PEM} \times V_o \quad (29)$$

The fuel cell efficiency is introduced in[19] as:

$$\eta_{fc} = \frac{2 \cdot F \cdot P_{fc}}{N_c I_{PEM} \Delta H} = \frac{0.6795 \cdot P_{fc}}{N_c I_{PEM}} \quad (30)$$

where $F=96485.4$ C/mol which represents the Faraday constant, and $\Delta H= 284000$ J/mol is the chemical reaction energy. In addition, the required hydrogen by the PEMFC is expressed using the following equation [205]

$$n_{H2} = \frac{P_{fc}}{2 F U_f V_o} \quad (31)$$

where U_f is the utilization factor, which is 0.85 based on [206,207].

Based on the above equations, we can build and analysis PEMFC model. The model presented here required specific parameters to be assigned to the computer simulation, as shown in Table 4. These parameter values are based on the manufacturing data [208] and similar literature [55] for the same system.

Table 4. Parameters values for BSC 500-W fuel cell.

Parameter	Value	Unit	Parameter	Value	Unit
N_{nc}	32	NA	T_{PEM}	333	K
A	64	cm ²	ξ_1	-0.948	NA
l	178	micro-m	ξ_3	7.6E-5	NA
J_n	3	mA/cm ³	ξ_4	-1.93E-4	NA
J_{max}	469	mA/cm ³	I_{PEM}	30	A
R_c	0.0003	ohm	β	0.016	NA
P_{O_2}/P_{H_2}	0.2095/1	atm	λ	23	NA

3.2 Fuel Cell Model Integrated with UAV

In general, UAVs consist of three main components: avionics, airframe, and propulsion system. The primary goal of this research is to supply the drone's power from a fuel cells propulsion system. To analyze the drone performance under the proposed propulsion system, reference drone data were used and collected from ref [209]. The flight mission specifications must be determined early in the design process of a drone. A fuel cell-powered drone's mission criteria can include takeoff, cruise, climb, and landing. The design analysis is conducted with a constrained analysis of conventional aircraft equations. The operational altitude is low, and the change in the aircraft weight during missions is small due to the low molecular weight of hydrogen. The UAV and its PEMFC system can operate under different

weather conditions. The mathematical model formulas for the wing loading and power-to-weight ratio of takeoff, climb, cruise, maximum speed, and stall speed are introduced in ref [207].

When thrust overcomes drag force during takeoff, the relationship between wing loading and power-to-weight ratio may be described as [207] :

$$\frac{P_{to}}{W_{to}} = \frac{k_{to}^3}{2 \times g \times D_{to} \times \eta_p} \times \left(\frac{2}{\rho_{0m} \times C_{Lmax}} \frac{W_{to}}{S_w} \right)^{\frac{3}{2}} \quad (32)$$

For the other flight mission conditions, the power-to-weight ratio can be calculated as follows:

For cruise:

$$\frac{P_{cl}}{W_{to}} = \frac{1}{\eta_p} \left(RC + \frac{1}{\frac{C_L}{C_D}} \times \sqrt{\left(\frac{2}{\rho_{100m}} \right) \times \frac{1}{\sqrt{C_{Dmin} \times \pi \times AR \times e}}} \times \sqrt{\frac{W_{to}}{S_w}} \right) \quad (33)$$

For cruise mission:

$$\frac{P_{cr}}{W_{to}} = \frac{V_{cr}}{\eta_p} \times \left(\frac{C_{Dmin} \times q_{cr}}{\frac{W_{to}}{S_w}} + \frac{\frac{W_{to}}{S_w}}{q_{cr} \times \pi \times AR \times e} \right) \quad (34)$$

For maximum speed mission:

$$\frac{P_{vmax}}{W_{to}} = \frac{V_{vmax}}{\eta_p} \times \left(\frac{C_{Dmin} \times q_{vmax}}{\frac{W_{to}}{S_w}} + \frac{\frac{W_{to}}{S_w}}{q_{vmax} \times \pi \times AR \times e} \right) \quad (35)$$

For stall conditions:

$$\frac{W_{to}}{S_w} = \frac{1}{2} \times \rho_{0m} \times V_s^2 \times C_{Lmax} \quad (36)$$

Where k , ρ_{0m} , η_p , RC , AR , e , V , and q are velocity ratio, air density at sea level, propulsion efficiency, rate of climb, aspect ratio, Oswald efficiency number, speed, and dynamic pressure. The mission requirement and the input parameters are mentioned in Table 5. The input parameters are considered for the small UAVs type that have a take-off weight from 4 to 20 kg.

Table 5. Input parameters and flight mission requirements for small-size (4-20 kg) PEMFC-UAV.

FC output (W)	250	C_L/C_D	14.6
Wing area (m ²)	0.89	e	0.85
Wingspan (m)	3	D_{to}	Launch by hand
MTOW (kg)	6.5	k_{to}	1.2
Aspect ratio	10.11	η_p	0.85
Stall speed (m/s)	10	ρ_{0m} (kg/m ³)	1.225

C_{Dmin}	0.025	$\rho_{100m} \text{ (kg/m}^3\text{)}$	1.213
C_{Lmax}	1.2	$\rho_{200m} \text{ (kg/m}^3\text{)}$	1.202
RC (m/s)	2-3	Altitude h (m)	200

The small PEM fuel cell UAV is composed of an airframe, avionics, hydrogen storage fuel, fuel cell stack, and battery. The take-off weight of a UAV powered by PEM fuel cells can be estimated as follows [207]:

$$W_{to} = W_{af} + W_{av} + W_h + W_{fc} + W_{batt} \quad (37)$$

Given that there are far less small UAVs with PEM fuel cell system than UAVs with conventional propulsion system, and UAV data is hardly made public, the airframe and avionics weights were simply estimated to equal 46% and 10% of the takeoff weight, respectively. The hydrogen weight can be calculated as follows:

$$W_h = \frac{\frac{P_{cr}}{W_{to}} \times (t_{to} + t_{cl} + t_{cr} + t_{vmax}) \times W_{to}}{ED_h} \quad (38)$$

Where t and ED_h are the time required for different missions and the gravimetric energy density of hydrogen, respectively. The relationship between power and gravimetric power density is evaluated using Aerostaks data, developed by horizon fuel cell technologies [207]. The weight of the fuel cell stack can be estimated as [207]:

$$W_{fc} = \frac{\frac{P_{cr}}{W_{to}}}{0.126 \times \frac{P_{cr}}{W_{to}} + \frac{373.78}{W_{to}}} \quad (39)$$

3.3 Battery Model integrated with Rotor UAV

Small UAVs are widely operated in a variety of fields (including military, commercial and daily life) due to their tiny volume, light wight, cheap cost, and flexibility. Most small UAVs use batteries to operate their propulsion system. Batteries have high reliability, simple operation, and ease of maintenance and transportation. However, they have lower energy density than other fuel cells or fossil fuels. Hence, UAVs powered by batteries have limited flight endurance [210]. Rotary UAVs are widely used in various fields due to their capability of low-speed flight, hovering, and high maneuverability. However, they consumed higher power than fixed-wing UAVs. Such UAVs are available with a variety of rotor numbers and/or configurations, with a greater number of rotors resulting in enhanced payload capabilities at the expense of increased power consumption and hence endurance[211]. In this section, the power consumption and flight endurance of a rotary UAV powered by LiPo batteries are discussed. The Staaker BG-200 UAV shown in Figure 38 is used as a case study.



Figure 38. Staaker- BG-200 UAV.

The rotor hover power P_r for a single rotor can be estimated as in ref [211]:

$$P_r = \frac{T^{\frac{3}{2}}}{\eta_R r_P \sqrt{2\rho_\alpha \pi}} \quad (40)$$

Where T is the required thrust, η_R is the rotor figure of Merit (FM) which is the ratio between the ideal and actual hover power, r_P is the radius of propeller, and ρ_α is the air density. Assuming the thrust is equally distributed between rotors, the total thrust can be equal to the weight, $T=mg$; hence, the hover power P_r for N_R rotors will be:

$$P_r = \frac{m^{\frac{3}{2}} g^{\frac{3}{2}}}{\eta_R r_P \sqrt{2 N_R \rho_\alpha \pi}} \quad (41)$$

Power consumption grows exponentially with mass, is inversely related to propeller radius, and reduces as the number of rotors increases. These elements, however, are not independent.

The mass of a propeller increases as its radius increases. A larger propeller takes up more space and necessitates longer and heavier arms. Increasing the number of rotors immediately adds bulk and demands more space, as well as the negatives already noted.

Abdilla et al. [211] investigated several battery models to arrive at an accurate estimation of effective battery endurance for usage in multirotor UAVs. In the trials, they employed a variety of commercially available three-cell (3S) Li-Po batteries and compared four models:

1. Ideal battery; $t = \frac{C_{nom}}{I}$;
2. Capacity offset $C_0 = 0.8$: $t = 0.8 \frac{C_{nom}}{I}$
3. Capacity offset $C_0 = 0.9$: $t = 0.9 \frac{C_{nom}}{I}$
4. Peukert equation: $t = \frac{C_{nom}^{np} R_{nom}^{np-1}}{I^{np}}$

Where np is Peukert exponent which is equal to 1.01.

The study found that an offset of 0.9 was the best fit, and the following equation will be used to calculate the energy capacity E as [211]:

$$E = k_B C_{nom} V_{nom} \quad (42)$$

where K_B , C_{nom} , and V_{nom} are the battery capacity offset factor, the rated battery charge, and the volt, respectively. K_B value can be estimated as 0.9. A linear variation of C_{nom}

With the battery mass is described as follow:

$$C_{nom} = 14.4 m_b - 0.14 \quad (43)$$

The UAV flight Endurance can be estimated as follows:

$$t = \frac{E}{P_r} \quad (44)$$

The mass and UAV size model was introduced in ref [212].

The mass of a UAV can be evaluated as the sum of fixed mass (m_{fixed}) and variable mass (m_V). The fixed mass includes a payload, battery, and control units. The variable mass includes the mass of the rotor, propeller, ESCs, arm, and their connectors components. We can write the total mass as:

$$m = m_{fixed} + m_V \quad (45)$$

If the mass of each arm is m_{arm} , and the sum of the mass of the remaining variable components per rotor is m_{var} then the total variable mass can be estimated as in ref [212].

$$m_V = \begin{cases} N_R(m_{var} + m_{arm}), & \text{in plane} \\ N_R(m_{var} + \frac{1}{2} m_{arm}); & \text{coaxial} \end{cases} \quad (46)$$

where a factor of $\frac{1}{2}$ is used in the coaxial case since the number of arms is half the number of rotors.

3.4 PV Model

Solar PV technology is used to produce electrical energy from the sun. In this section, an analytical model has been applied and validated against the manufacturer data shown in Table 6. A single-diode model is used, as represented in Figure 39.

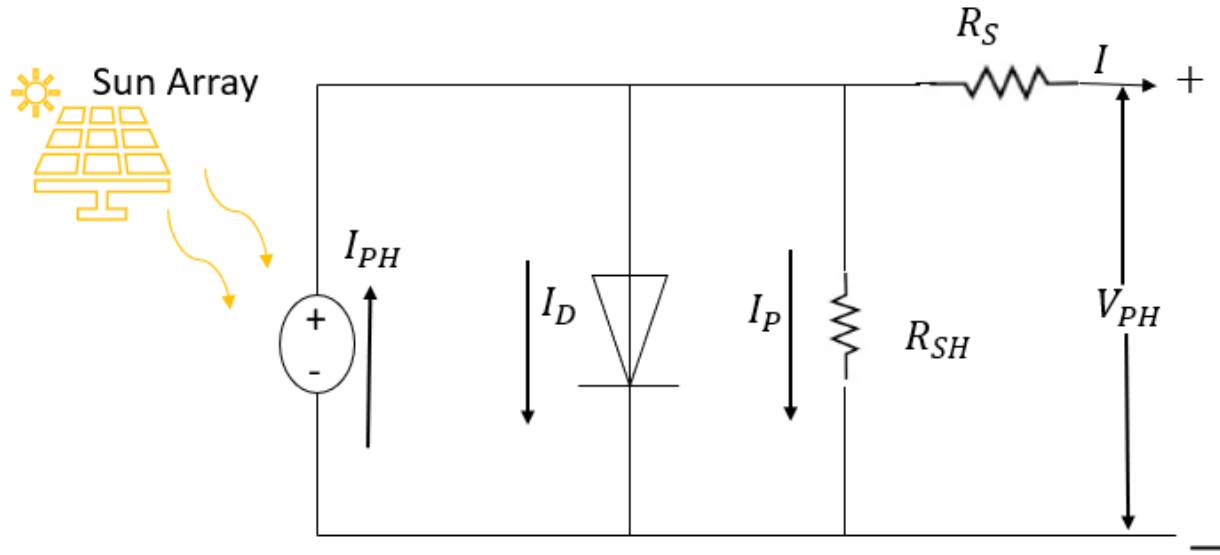


Figure 39. Model of PV cell.

A general mathematical model of PV has been introduced for over four decades. The I-V output characteristics of the PV are used for the MPPT technologies. The output current equation of a PV solar cell is described in Refs [213–215] as:

$$I = I_{PH} - I_D - I_P \quad (47)$$

where I_{PH} , I_D , and I_P are photonic currents generated by irradiance, diode current, and parallel resistance current in (A), respectively.

The out current then can be stated as follow:

$$I = I_{PH} - I_S \left[\exp \left(\frac{(V + IR_S)}{K T_C \alpha} \right) - 1 \right] - \frac{(V + IR_S)}{R_{SH}} \quad (48)$$

Where I_S represents the cell reversed saturated current, and V is the PV voltage. R_S and R_{SH} are series and shunt resistances of PV cells, respectively. K , T_C and α are Boltzmann constant ($= 1.38 \times 10^{-23} \text{J/K}$), cell temperature in Kelvin, and the ideal factor of p-n junction, respectively.

The photonics current is a function of temperature and solar irradiance G ; it can be calculated [216,217] as:

$$I_{PH} = [I_{Sc} + K_I (T_C - T_r)] \frac{G}{1000} \quad (49)$$

Where, I_{Sc} is the short circuit current. K_I represents the short circuit current coefficient. T_r is the cell reference temperature (k), and G is the solar irradiance.

The reversed saturation current of the cell is given by [217].

$$I_S = I_{RS} \left(\frac{T_C}{T_r} \right)^3 \exp \left(\frac{q E_G}{K \alpha} \times \left(\frac{1}{T_r} - \frac{1}{T_C} \right) \right) \quad (50)$$

Where I_{RS} is the reversed saturated current at a reference temperature T_r , and q is the electron charge ($= 1.6 \times 10^{-19} \text{C}$). E_G is the band gap energy of the cell which (for silicon) can be expressed as [218]:

$$E_G = E_{G,ref} [1 - 0.0002677 (T_C - T_r)] \quad (51)$$

Where $E_{G,ref} = 1.121 \text{ eV}$ for silicon.

The output current of a PV model with a combination of solar cells is expressed [216] as

$$I = N_P I_{PH} - N_P I_S \left[\exp \left(q \frac{(V + IR_S)}{N_S K T_c \alpha} \right) - 1 \right] - N_P q \left(\frac{V + IR_S}{N_S R_{SH}} \right) \quad (52)$$

Where the N_P and N_S are the number of parallel and series cells, respectively.

The most simplified equation of the generalized PV model [215] can be given by

$$I = N_P I_{PH} - N_P I_S \left[\exp \left(\frac{(qV)}{N_S K T_c \alpha} \right) - 1 \right] \quad (53)$$

The maximum power can be expressed as

$$P_{max} = V_{max} I_{max} \quad (54)$$

where V_{max} and I_{max} are the terminal voltage and current of the solar cell model at a maximum power point (MPP).

The efficiency of solar cells can be determined as [219]:

$$\eta_{sc} = \frac{P_{max}}{G_N A} \quad (55)$$

where G_N and A solar radiation intensity under standard conditions and solar cell surface area, respectively.

Table 6. Specifications of Sunpower SPR-X21-255 solar panel.

Cell technology	Monocrystalline Silicon
Number of cells in series	72
Reference cell temperature	25 C
Nominal cell temperature	41.5 C
Open circuit voltage, V_{oc}	51 V
Short circuit current, I_{sc}	6.3 A
Voltage at maximum power	42.8 V
Current at maximum power	5.95 A
Maximum power	255 W
Short circuit temperature coefficient k	2.52 mA/°C
Peak efficiency	20.5%

3.5 Solar Radiation Power for UAV

Many factors influence solar radiation, including geographical location, day and time, flight position, meteorological conditions, and ground and air reflectivity. Because of the properties of the solar vehicle, the calculation method is simplified in energy balance calculation. The

solar radiation is then computed using the simplified model, and parameters such as solar power can be determined.

The beam radiation G_H which can change with time and weather conditions, can be expressed as in ref [220].

$$G_H = G_{se} \tau_b \cos(\theta) \quad (56)$$

Where G_{se} is the extraterrestrial radiation intensity, τ_b is the atmospheric turbidity and θ is the solar beam incidence angle. The G_{se} can be evaluated as:

$$\begin{aligned} G_{se} = G_{sc} (1.00011 & \\ & + 0.034221 \cos B \\ & + 0.00128 \sin B + 0.000719 \cos 2B + 0.000077 \sin 2B) \end{aligned} \quad (57)$$

Where G_{sc} is the radiation constant (1367 W/m^2), and $B = (n - 1) \frac{360}{365} (^\circ)$, where n represents n -th day of the year $1 \leq n \leq 365$.

The atmospheric turbidity for a transparent atmosphere is expressed in [221]

$$\tau_b = a_0 + a_1 \exp(-k \times m) \quad (58)$$

where a_0, a_1, k are the turbidity coefficients, and m is the atmospheric mass related to the angle of incident of the beam, which can be calculated as:

$$m = \frac{1}{\cos(\theta)} \quad (59)$$

The formula of turbidity coefficients can be expressed as:

$$a_0 = 0.4237 - 0.00821 (6 - A)^2 \quad (60)$$

$$a_1 = 0.5055 + 0.00595 (6.5 - A)^2$$

$$k = 0.2711 + 0.01858 (2.5 - A)^2$$

The angle of the incident is described in detail in [221] and it is expressed as:

$$\begin{aligned} \cos \theta = & \sin \delta \sin \varphi \cos \beta - \sin \delta \cos \varphi \sin \beta \cos \gamma \\ & + \cos \delta \cos \varphi \cos \beta \cos \omega \\ & + \cos \delta \sin \varphi \sin \beta \cos \gamma \cos \omega \\ & + \cos \delta \sin \beta \sin \gamma \sin \omega \end{aligned} \quad (61)$$

where δ , φ , β , and ω are the sun declination angle, the latitude, the slope angle, and the hour of the sun, respectively. Considering the slope is very small ($\beta = 0$), the incidence angle becomes

$$\cos \theta = \sin \delta \sin \varphi + \cos \delta \cos \varphi \cos \beta \cos \omega \quad (62)$$

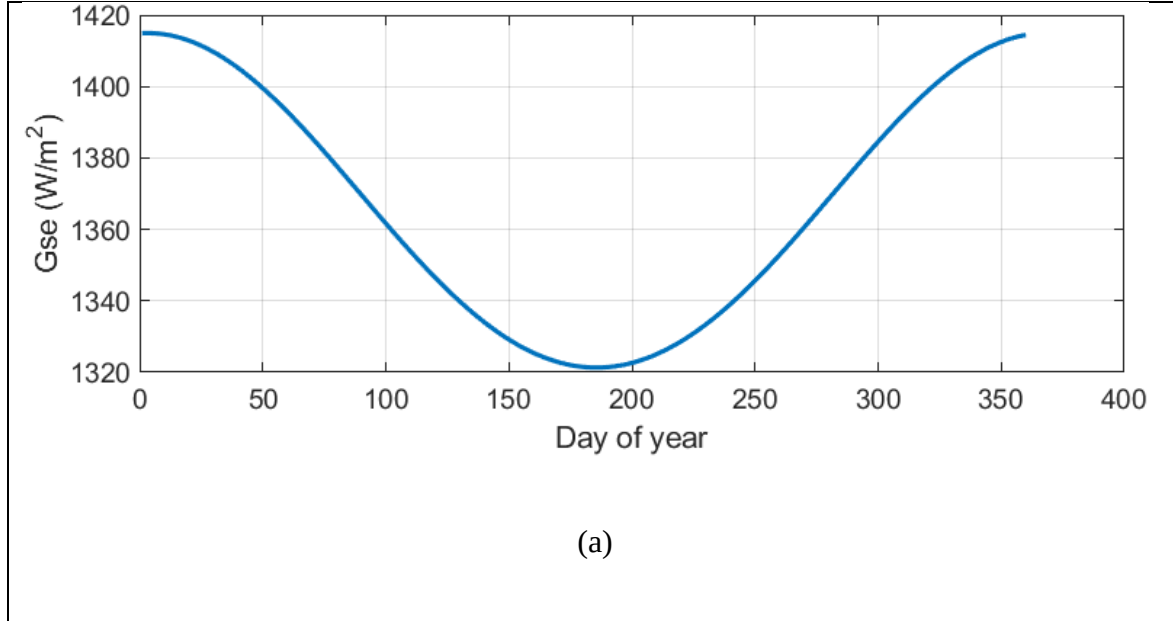
The sun declination angle is expressed as:

$$\delta = 23.45 \sin\left(360 \frac{284 + n}{365}\right) \quad (63)$$

For a more accurate equation, the declination angle, as it is suggested by ref [221]:

$$\delta = \frac{180}{\pi} (0.006918 - 0.399912 \cos B + 0.070257 \sin B - 0.006758 \cos 2B + 0.000907 \sin 2B - 0.002697 \cos 3B + 0.00148 \sin 3B) \quad (64)$$

In this study, the latitude angle is 26.23 °N (for Dhahran, KSA), and the flight altitude is 200 m. We can now address the fixed latitude and fixed beam incidence angle problems. Following the analysis and explanation showed above, the appropriate radiation turbidity τ_b and beam radiant intensity G_H at the specified date and time may be computed. The Extraterrestrial radiation intensity G_{se} and the beam of radiance intensity G_H can vary with the time of year, as depicted in Figure 40.



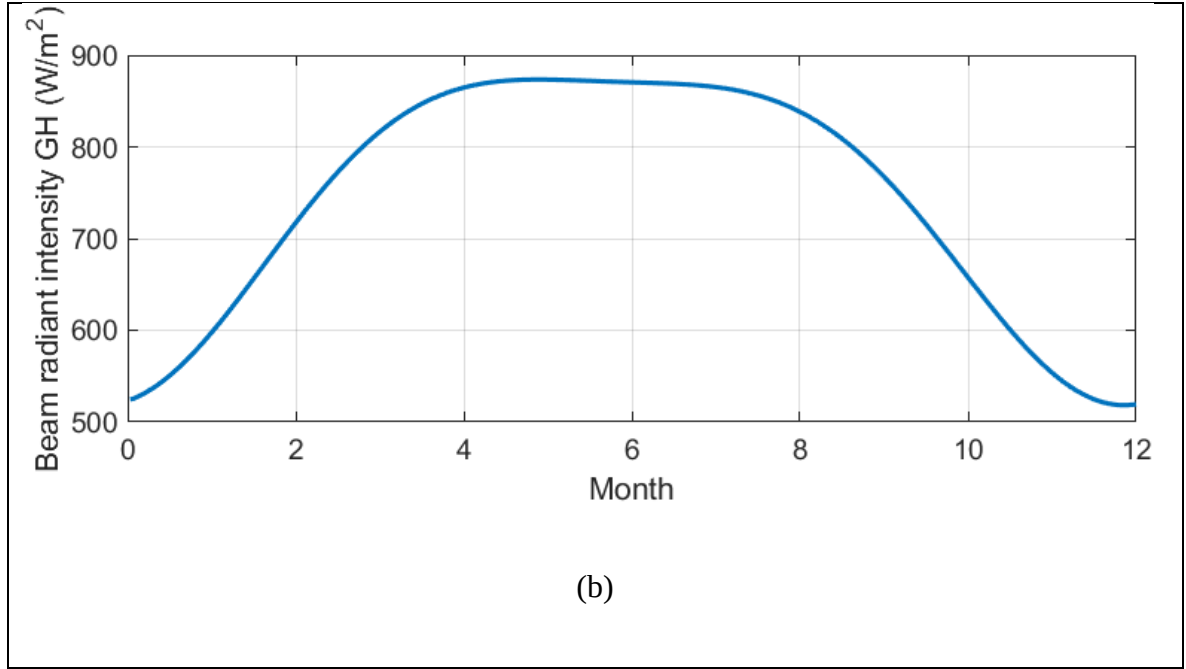


Figure 40. (a) Extraterrestrial radiation intensity G_{se} vs the day of year; (b) beam radiation intensity (G_H) for Dhahran city, KSA, vs month.

3.6 Hybrid Solar Model Integrated with UAV

The study of the output power and output balance of solar aircraft is critical to flying UAVs over long distances. Solar power must be analyzed since the plane requires electricity, and the changing trend of battery storage energy must be determined to evaluate the flying state of the UAV. The basic method for maintaining long-term flight for low-altitude long-season solar-powered UAVs is to maintain low-altitude level flight for maximum energy efficiency while also using solar cells to obtain energy from sunlight to charge the storage battery in the case of insufficient light intensity or continuous flight at night.

The output of solar power is expressed in the literature [220] as follows:

$$P_{SOLAR} = \eta_{sc} \eta_{MPPT} S_{sc} G_H \quad (65)$$

Where η_{sc} indicates the efficiency of solar cell panels, η_{MPPT} represents the MPPT efficiency, and the S_{sc} is the array area in m^2 . The array area can be assumed to be 85% of the wing surface area of the aircraft. The solar panels' mass should be considered when designing solar UAVs. This can be calculated as shown in [222] by:

$$m_{sc} = S_{sm}(k_{sc} + k_{enc}) \quad (66)$$

Where k_{sc} & k_{enc} are the density of the solar cell surface area and the encapsulation respectively. The array area S_{sm} can be either estimated as 85 % of wing surface area, or for accurate estimate, it can be calculated as follow:

$$S_{sm} = \frac{\pi}{2 \eta_{sc} \eta_{cbr} \eta_{mppt} I_{max} \eta_{wthr}} \left(1 + \frac{T_{night}}{T_{day} \eta_{dchr} \eta_{chrg}} \right) P_{tot} \quad (67)$$

Where η_{sc} , η_{cbr} , η_{mppt} , I_{max} , and η_{wthr} represent solar cell efficiency, Efficiency of cambered configuration, MPPT efficiency, maximum irradiance, and weather margin factor.

The maximum power required at the MPPT level is expressed by the maximum power output of the modules, which is proportional to their area. This can be expressed as:

$$m_{mppt} = k_{mppt} P_{SOLAR_max} \quad (68)$$

Where k_{mppt} is the mass to power ratio of MPPT. The maximum solar power can be achieved at the maximum solar irradiance (G_H).

For level flight, the aircraft thrust is equal to the drag, and the lift is equal to the aircraft weight, this can be expressed as:

$$T = D = \frac{1}{2} \rho V^2 S C_d \quad (69)$$

$$W = mg = L = \frac{1}{2} \rho V^2 S C_l \quad (70)$$

Where, ρ is the air density, V is the velocity, S is the wing area, g is the earth gravitational constant, and m is the total mass of the aircraft. C_d and C_l represents the drag and lift coefficients respectively.

The level flight power is expressed then as:

$$P_{level} = TV = \frac{C_d}{C_l^{\frac{3}{2}}} \sqrt{\frac{2 (mg)^3}{\rho S}} \quad (71)$$

In term of aspect ratio (AR) and wingspan (b), the level flight power can be evaluated as:

$$P_{level} = TV = \frac{C_d}{C_l^{\frac{3}{2}}} \sqrt{\frac{2 AR g^3}{\rho}} \frac{m^{3/2}}{b} \quad (72)$$

The total required power of the UAV can be calculated by the following expression

$$P_{tot} = \frac{P_{level}}{\eta_{prop}} + P_{avionic} + P_{payload} \quad (73)$$

The mass of the battery is directly related to the amount of energy it must store, which is the product of energy consumed and night length, and inversely proportional to its gravimetric energy density.

$$m_{batt} = \frac{T_{night}}{\eta_{dchrg} k_{batt}} P_{tot} \quad (74)$$

The total daily energy consumption of the battery is given by:

$$E_{elec_tot} = \left(T_{day} + \frac{T_{night}}{\eta_{dchrg} \eta_{chrg}} \right) P_{tot} \quad (75)$$

CHAPTER 4 RESULTS AND DISCUSSION

In this section, three renewable power sources are introduced and discussed. The fuel cell model performance is studied for PEMFC under different performance parameters. The model is integrated into a fixed-wing UAV and validated against the real data from reported experiments and manufacturers. The UAV is integrated with a fuel cell system and a LiPo battery. The fuel cell is the primary source, and the battery's role is to operate at a high response, such as climbing and maneuvering. Generally, required power and endurance are studied and optimized. An optimization process is introduced for UAV-based FC power. Additionally, the battery required power and endurance are investigated for a multi-rotor coaxial drone. Moreover, PV performance under different conditions and at different regions and times is analyzed and discussed. Then, hybrid solar cells with a battery are integrated with a small fixed-wing UAV. Finally, all results and discussion of each model are based on the mathematical models mentioned in chapter 3.

4.1 Fuel Cell Model Analysis

In this section, the fuel cell model validation and performance are discussed and analyzed. The fuel cell then is integrated with a UAV to study the power and endurance performance of the UAV. Finally, an optimization process is introduced to evaluate the optimal power and endurance based on different UAV design parameters.

4.1.1 Fuel Cell Model validation

Using the parameters data shown in Table 4, the PEMFC validation is presented in Figure 41. The PEMFC is validated by verifying the polarization curve obtained from the mathematical model and tested against the manufacturer's data of the BSC-500 fuel cell. The polarization curve shown in Figure 41 has an excellent agreement with the real data. It can be indicated that the validation results show that the mathematical model has the potential to assess the effectiveness of the UAV propulsion system.

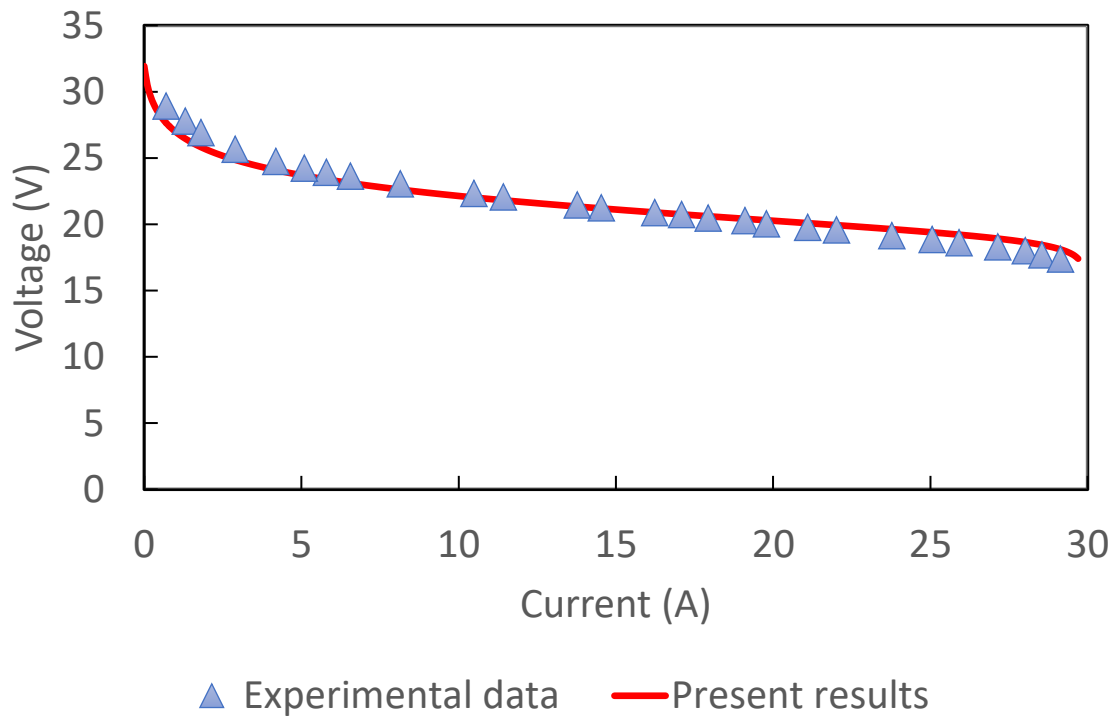


Figure 41. Validation of the present results against the experimental data if BSC 500 fuel cell in term of the polarization curve.

4.1.2 Fuel Cell Simulation Results and Analysis

Figure 42 depicts the performance of fuel cell in terms of PEMFC current flowing through the cell. The output power is determined from the product of voltage and current. The open circuit voltage ideally follows the Nernst voltage until it reaches an optimal voltage, then the voltage drops due to

the over-potential losses. The over-potential losses grow with increased current flowing through the fuel cell and have a bigger negative influence on fuel cell performance. The effect of activation overpotentials on decreasing fuel cell voltage rises with increasing current. Thus, as the current grows, the PEM fuel cell voltage lowers, and the output power fluctuates between growing and decreasing. This is due to the fact that the rate of rise in current is larger than the rate of drop in voltage, resulting in greater PEMFC output power. However, by flowing greater currents through the FC, the concentration over-potentials grow, resulting in a significant decrease in PEM fuel cell output. As a result, activation and concentration over-potential values are crucial for low and high current levels, respectively. Therefore, a proper balance between the current flowing through the fuel cell and its producing capacity must be established [223].

The analytical results shown in Figure 42 indicate that by increasing the fuel cell current from 5 to 10 A, and from 25 to 30 A, the PEM fuel cell output voltage decreases by 7 % and 18.44 %, respectively. Similarly, for the same conditions, the power increases and decreases by 86.93 % and 2.13 %, respectively. This implies that the decrease in PEM fuel cell performance is more noticeable at lower current levels since the activation over-potential inhibits the fuel cell voltage from reaching the optimum voltage at lower current values.

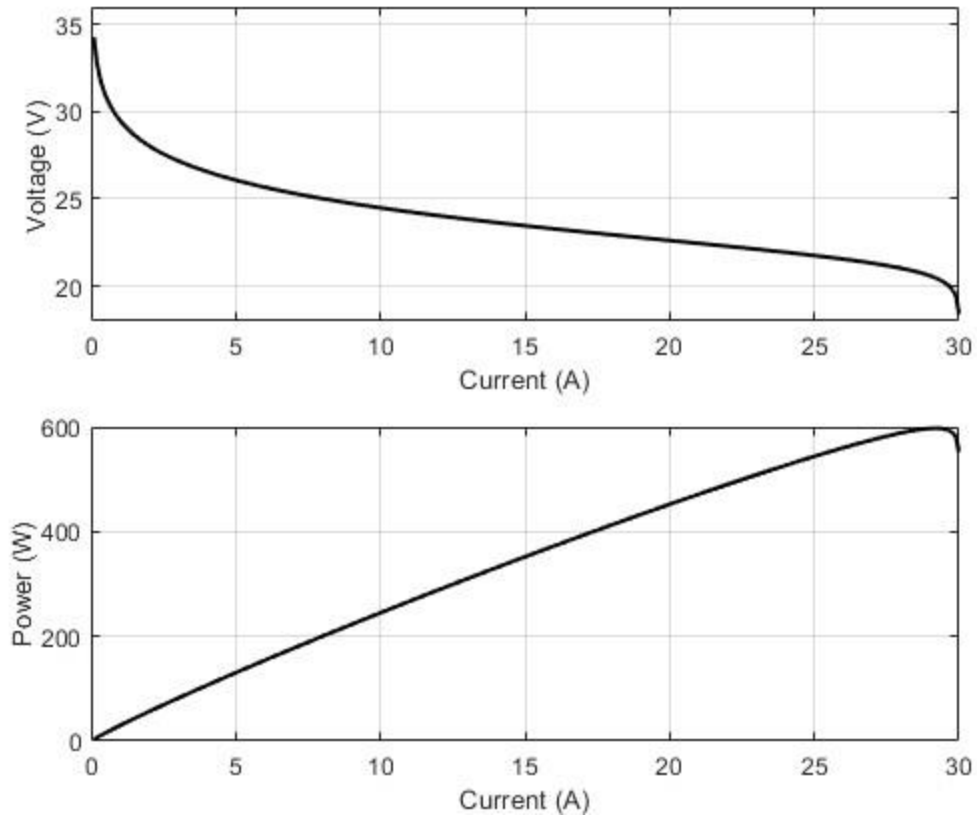


Figure 42. PEMFC voltage and power versus current.

Moreover, Figure 43a indicates that the increase in the current results in decreasing the fuel cell efficiency. For instance, increasing the fuel cell current from 5 to 10 A and from 25 to 30 A, results in efficiency drops of 7 and 18.4 %, respectively. Also, the increase in power leads to decreasing efficiency. Similarly, Figure 43b indicates that when the current changes from 5 to 10 A and from 25 to 30 A, it leads to 104 and 19.6 % increases in the rate of required hydrogen by the fuel cell, respectively. The reason is that, at greater current rates, the required output power is reduced, requiring less hydrogen fuel. For UAV applications, the objective is to deliver the required power while maintaining high efficiency and minimizing losses. Consequently, increasing the process FC current achieves the intended result. However, raising the current through the PEMFC excessively might increase the heat

created in the stack by increasing chemical reactions. This is hazardous to the propulsion system and has the potential to destroy the entire system. As a result, a proper balance must be formed by taking into account all of the aspects influencing the performance of the propulsion system. This may be accomplished by changing the current in the ohmic zone and away from the concentration region.

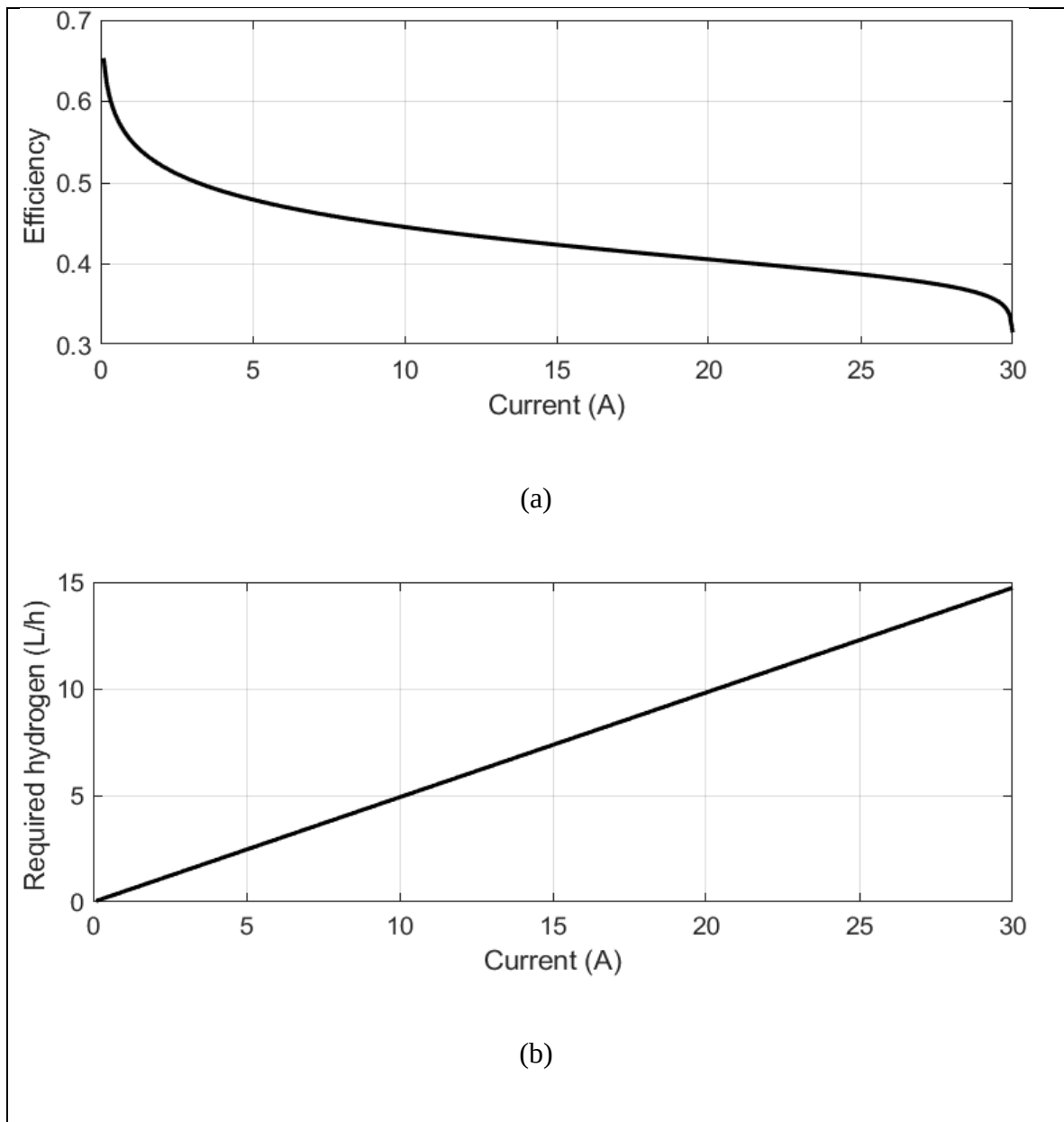
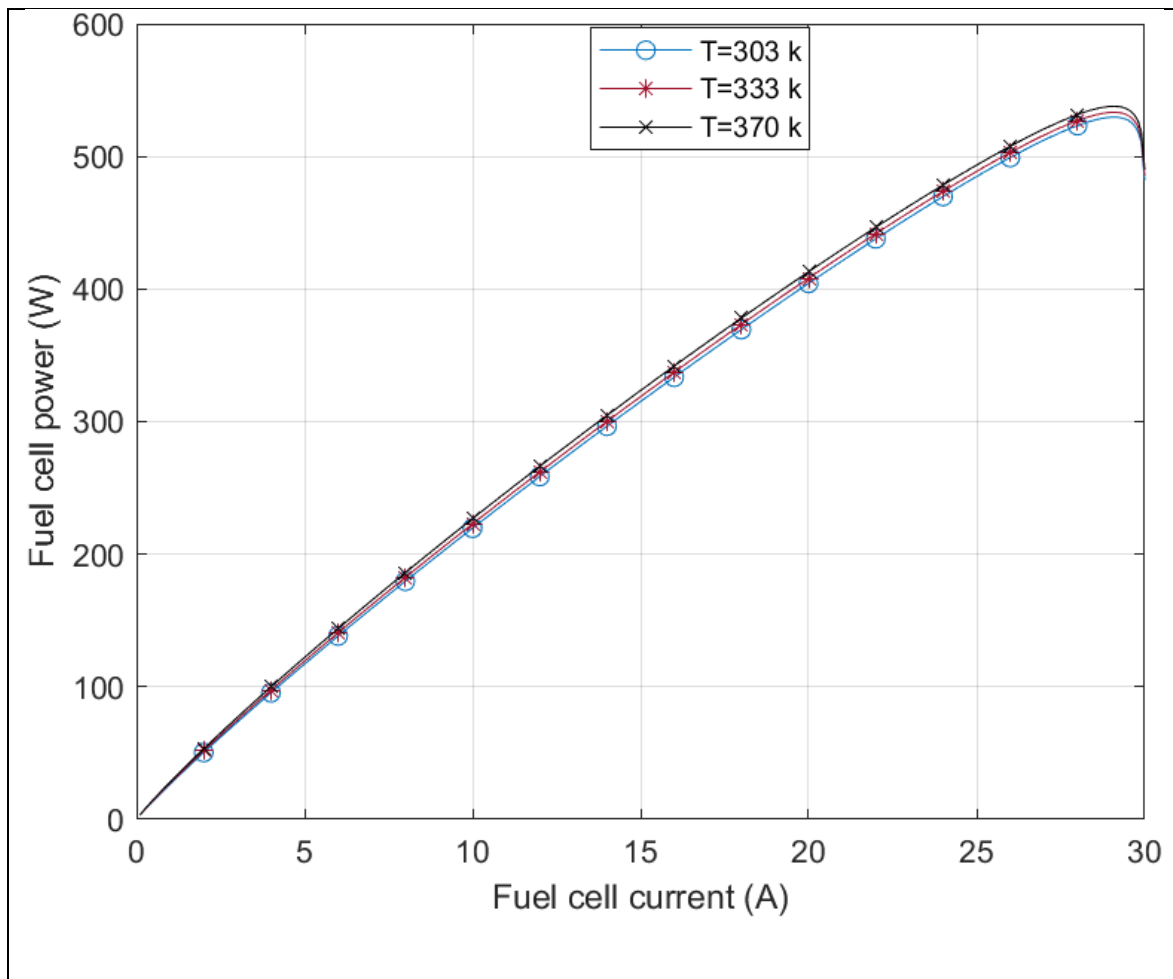


Figure 43. The effect of PEM FC current on a) efficiency, and b) Required hydrogen by the fuel cell.

The output power and efficiency can be affected by the operating fuel cell temperature, as illustrated in Figure 44. This affect is because increasing the value of operating temperature can cause an increase in ionic conductivity, high electrode reaction, and high effective gas diffusion coefficient [224], hence, the power and efficiency will be increased. This can increase the total power and overall efficiency of the propulsion system. However, this increase has consequences of reducing lifetime and increasing the propulsion system cost. Fortunately, unlike SOFC, PEM fuel cells operate at low temperatures. As shown in Figure 44, when changing the operating PEMFC temperature from 303 to 370 K (at a current 15 A), the output power and efficiency enhanced slightly by 1.36 and 1.35 %, respectively.



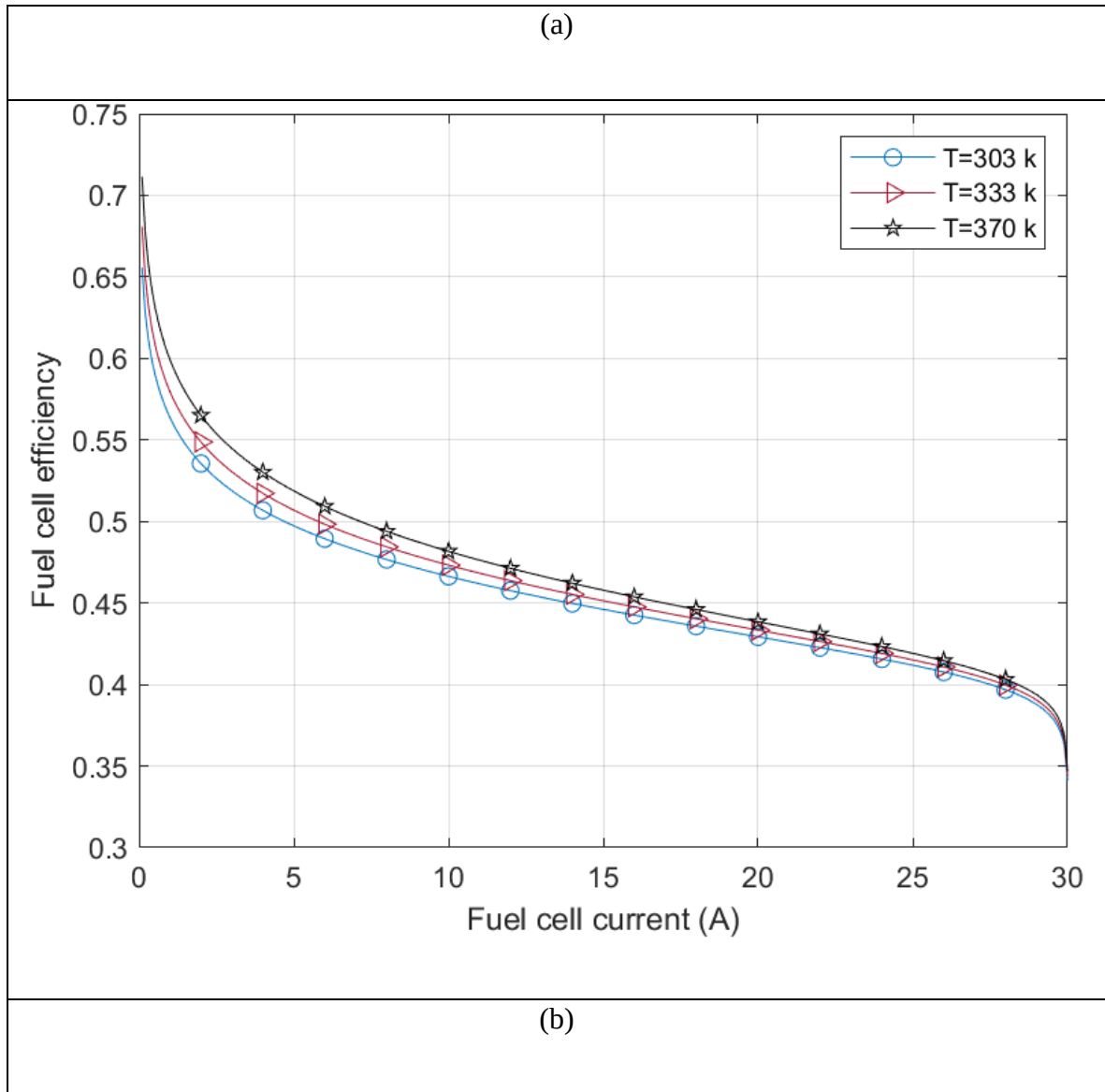
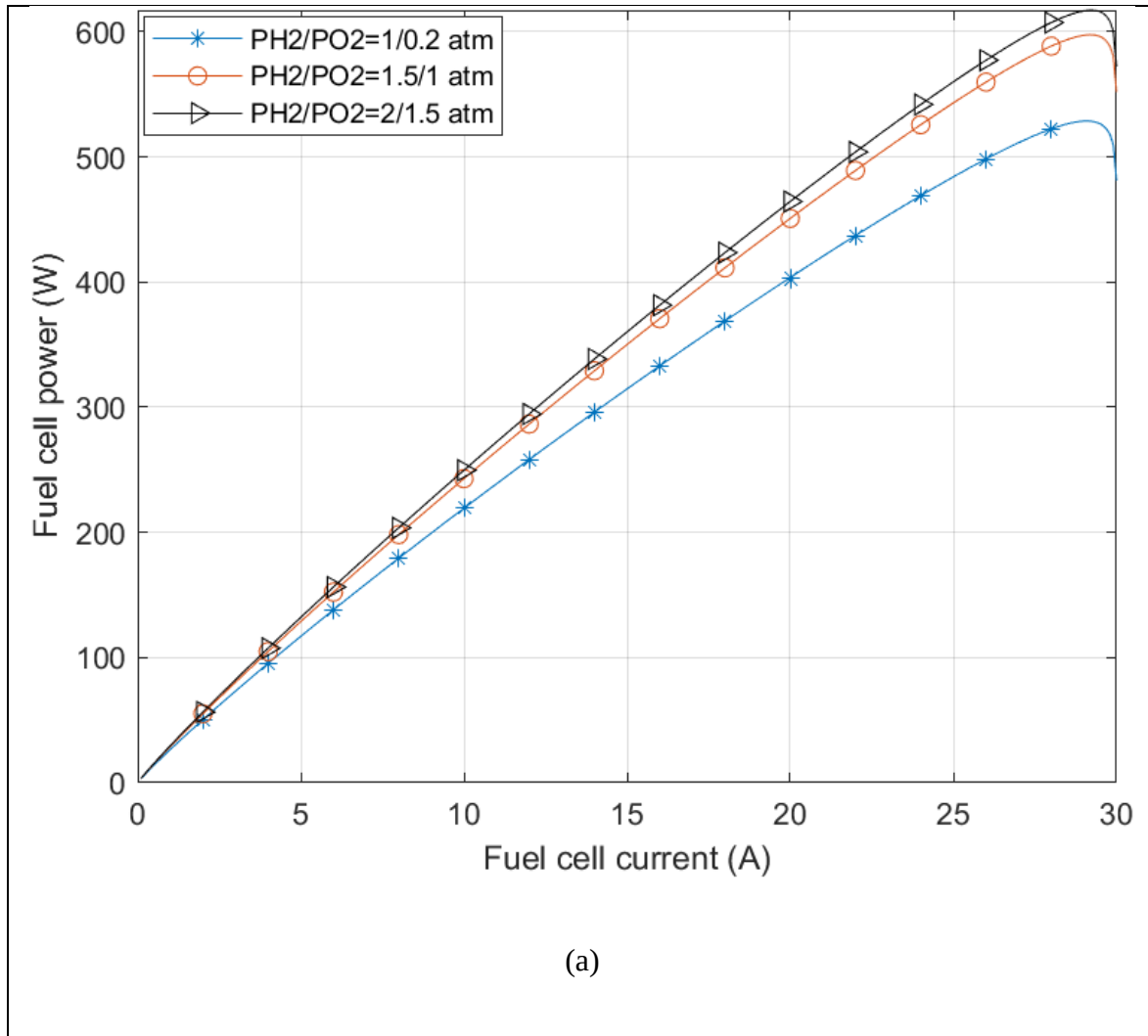


Figure 44. The effect of temperature on fuel cell's a) power and b) efficiency.

The increase in partial pressure of hydrogen and oxygen can cause the activation losses and concentration of fuel cell to decline, enhancing the equilibrium voltage. The explanation is that the concentration loss is reduced, the molar diffusion rate is increased, and the reactivity of the porous electrode is increased. As a result, raising the PEMFC partial pressures improve the overall performance and output power of the fuel cell. In general, increasing the working pressure is preferable to improve the performance of the

propulsion system. However, this causes an increase in power consumption. Figure 45 indicates that by increasing the partial pressures P_{H_2}/P_{O_2} from 1.0/0.2 to 2.0/1.5 atm (at a current 15 A), the output power and overall efficiency of the fuel cell system are improved by 17.9 and 17.6 %, respectively.



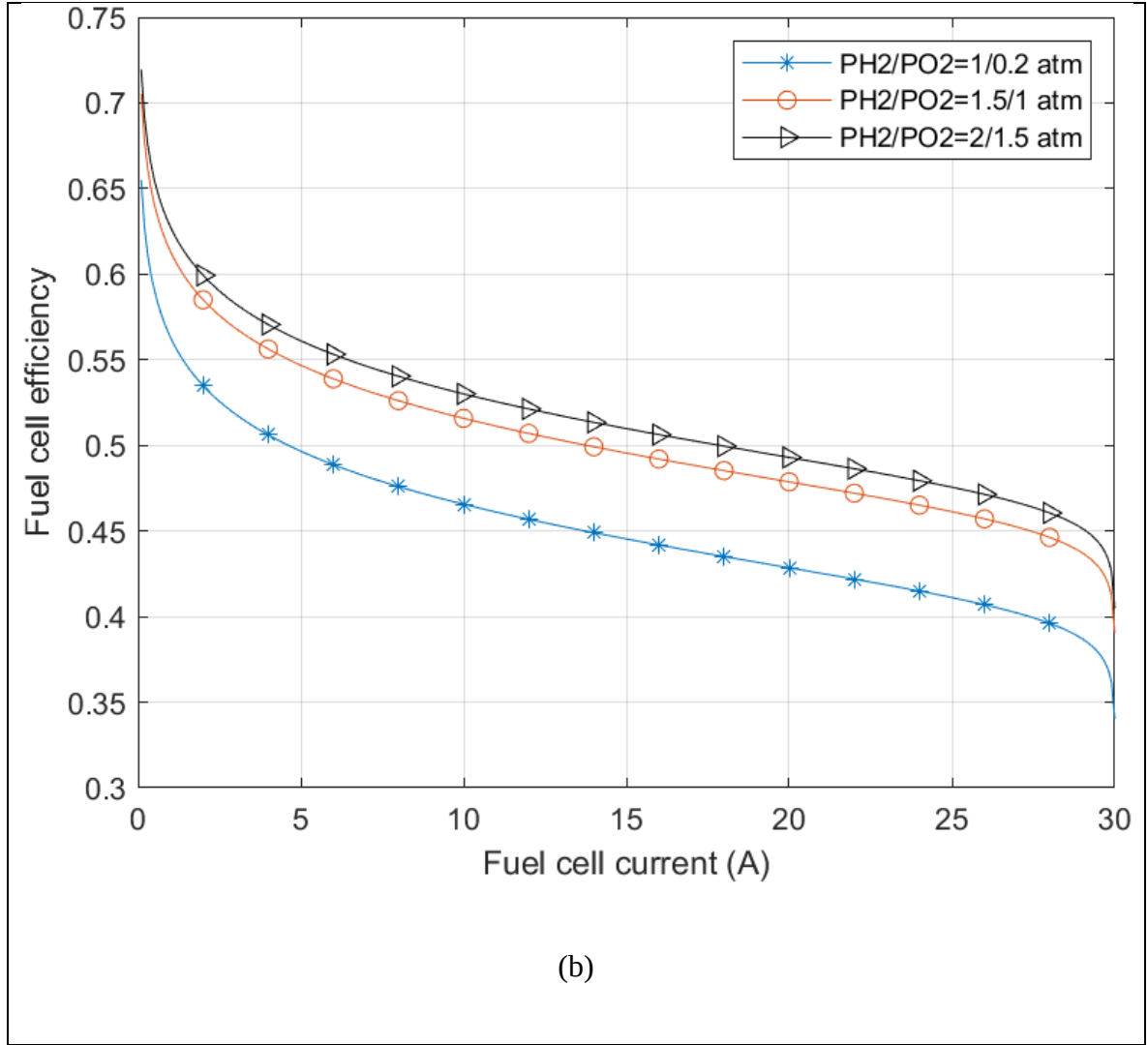


Figure 45. The effect of partial pressure on fuel cell's a) power, b) efficiency.

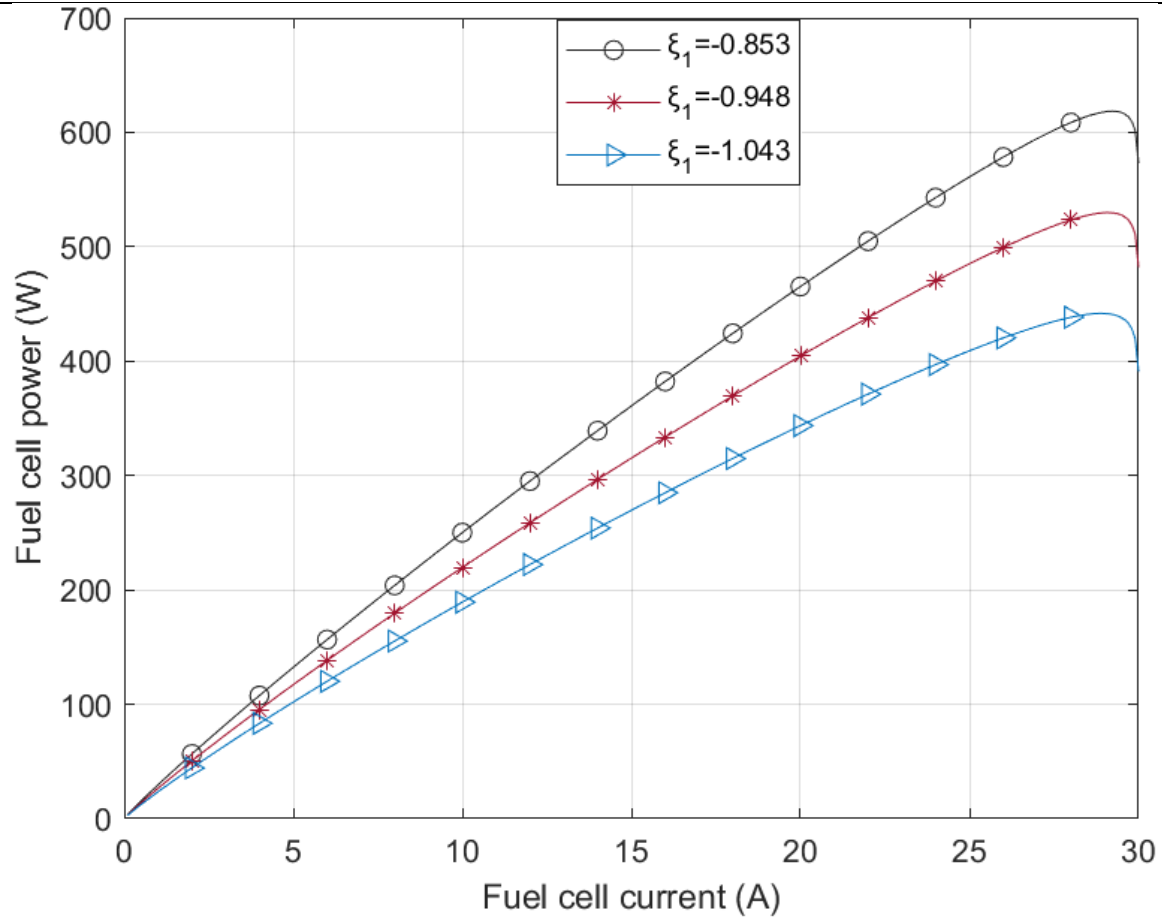
The parametric coefficients (ξ_i) values for each cell model are defined based on theoretical equations mentioned in section 3.1 with electrochemical, kinetic, and thermodynamic fundamentals [225]. For instant, ξ_1 and ξ_3 are affected by all current values in the same high order, and they are highly sensitive parameters [59]. The exact electrochemical definition of ξ_i and ξ_t are as follows [226]:

$$\xi_1 = \frac{\Delta G_a}{2 \cdot F} - \frac{\Delta G_c}{\alpha_c \cdot n \cdot F} \quad (76)$$

$$\xi_3 = \frac{R \cdot (1 - \alpha_c)}{\alpha_c \cdot F} \quad (77)$$

where ΔG_a and ΔG_c are free activation energy for the standard state (J/mol) referred to the anode and cathode, respectively. α_c is the parameter for the cathode chemical activity.

Figure 46 & Figure 47 illustrate the effect of ξ_1 and ξ_3 on output power and efficiency respectively, and the results show that ξ_1 has more impact on the FC performance than ξ_3 . Figure 46a indicates that by changing the value of ξ_1 from -1.04 to -0.853 (at a current =15A), the output power and overall efficiency increase by 32.7 and 46.2 %, respectively. Similarly, by changing the value of ξ_3 from 8.37×10^{-5} (at a current =15A), the output power and overall efficiency increase 10 and 10.5 %, respectively (see Figure 47).



(a)

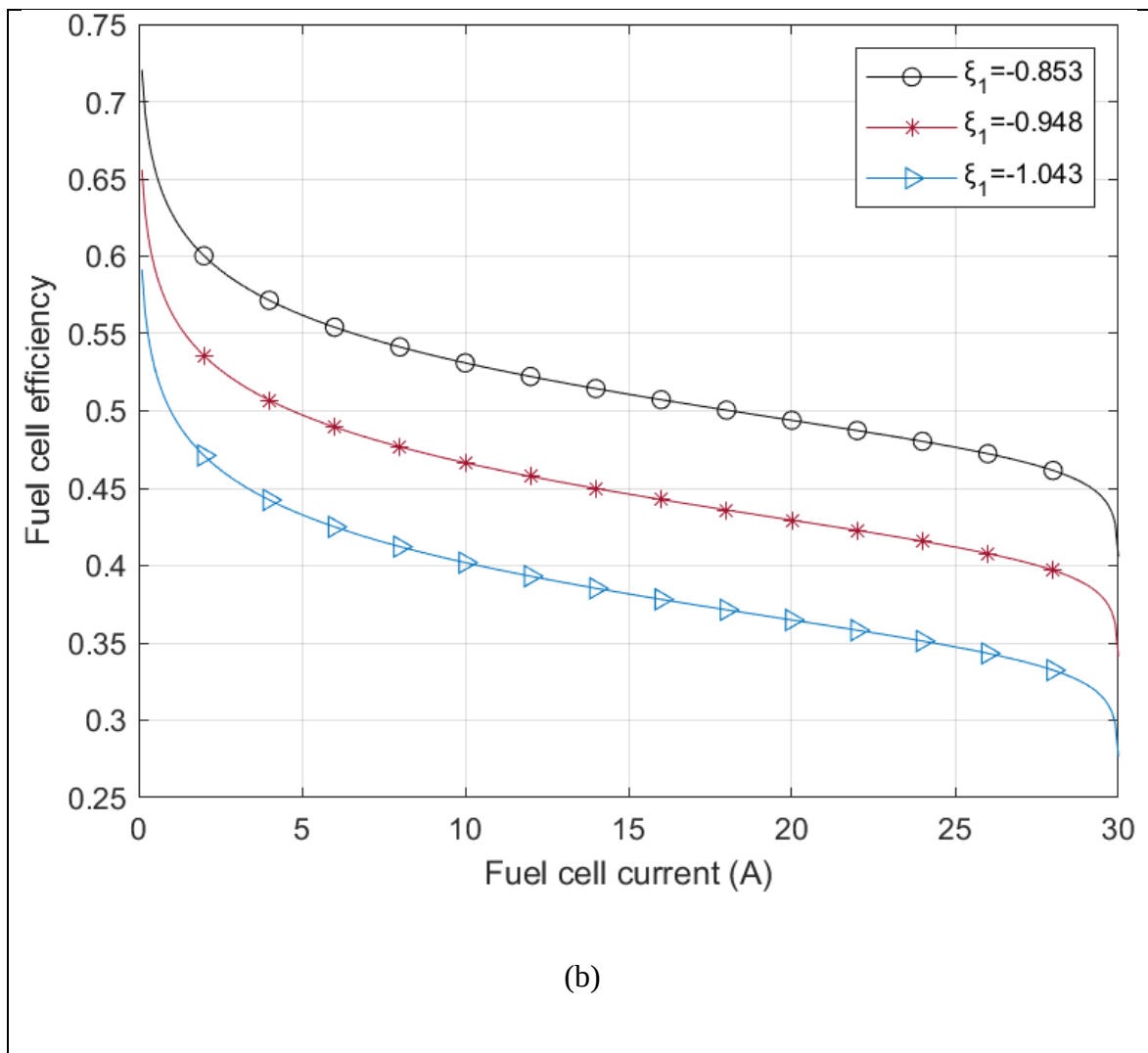
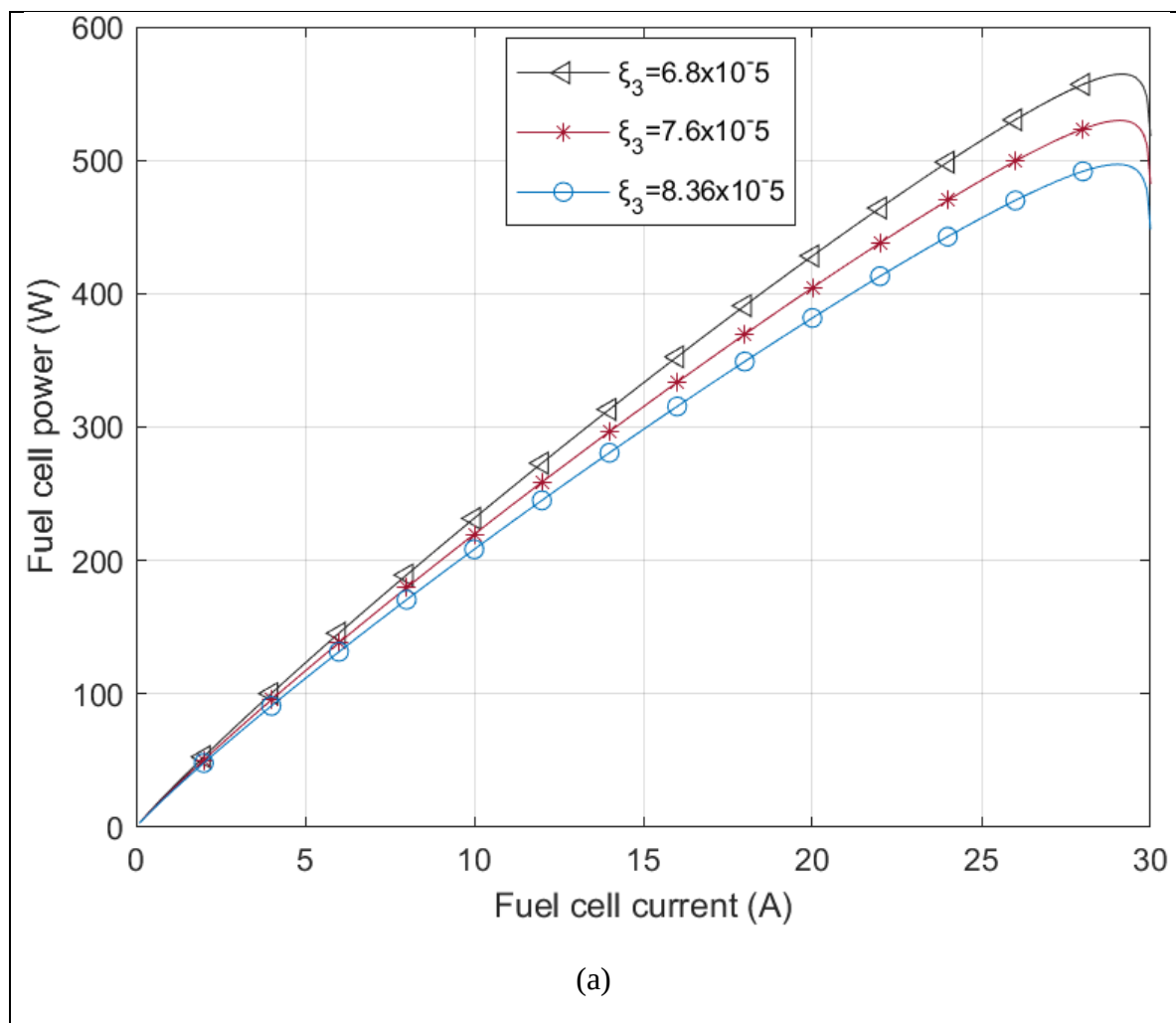


Figure 46. The effect of ξ_1 on (a) power; (b) efficiency.



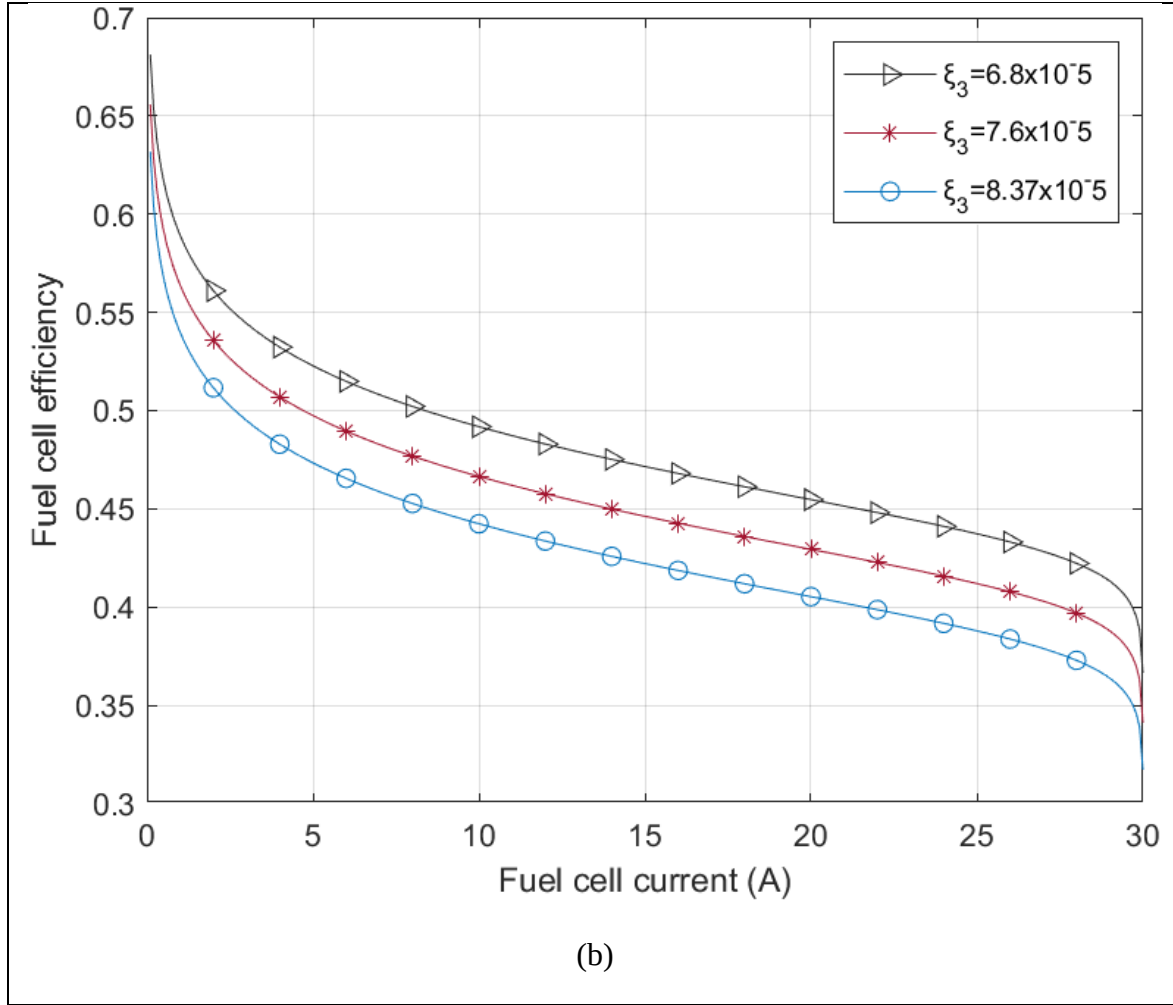


Figure 47. The effect of ξ_3 on (a) power; (b) efficiency.

4.1.3 Fuel Cell UAV Performance and Discussion

Wing loading and power-to-weight ratios with a 30 % margin are presented in Figure 48 for take-off, climb, cruise, and maximum speed missions. The performance is evaluated based on the power output for different flight phases. The output power for each mission can be determined from the design constrain plot at a wing loading of 65 N/m². The output power is indicated in and compared to the actual values shown in Table 7. The proposed model achieves a reduction of take-off and cruise power conditions by 11.65 and 36.25 % to the

actual model. At the same time, the power at the climb mission increases by 6.57 %. Reducing power consumption is favorable for obtaining more fuel cell lifetime.

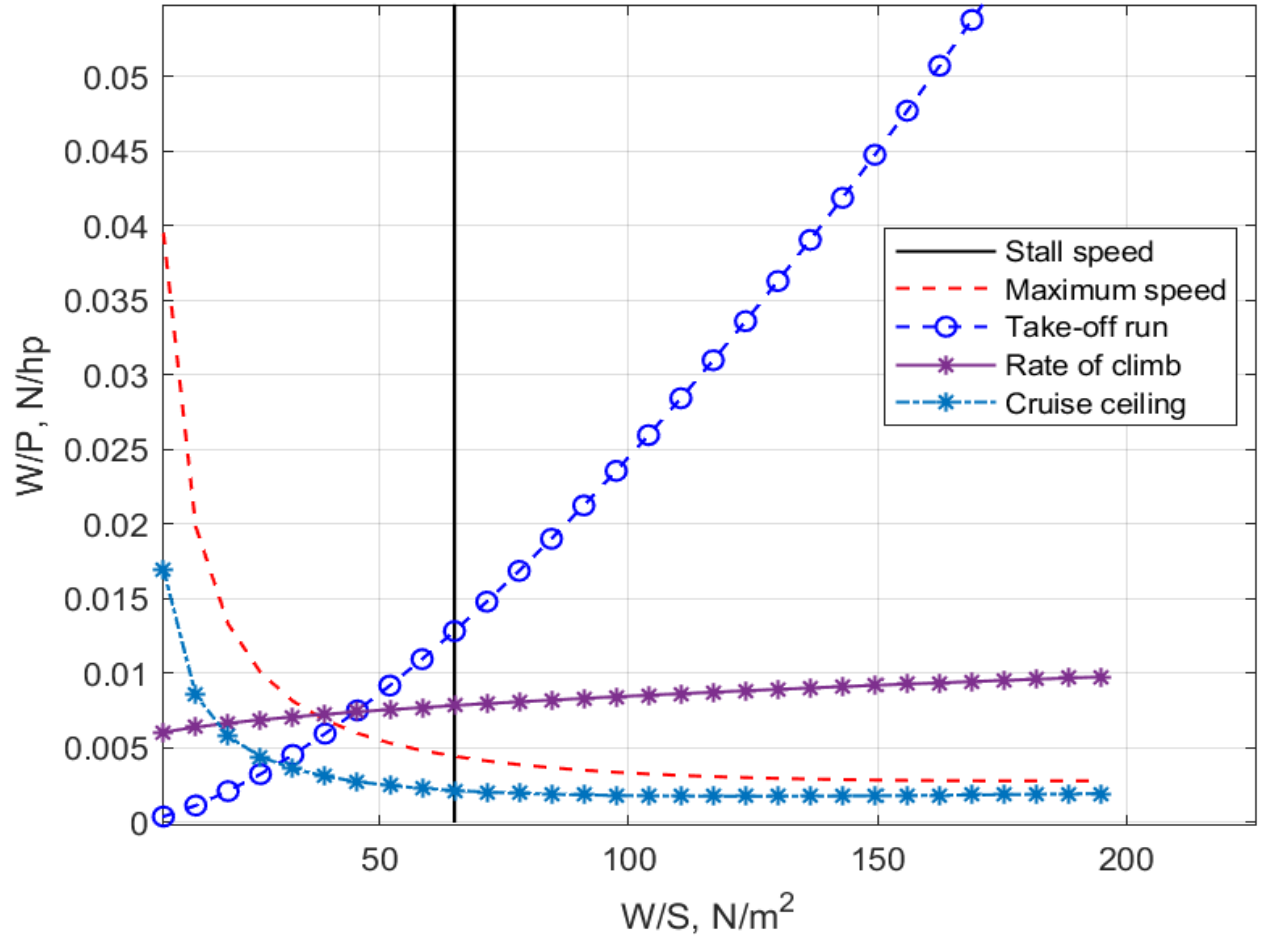


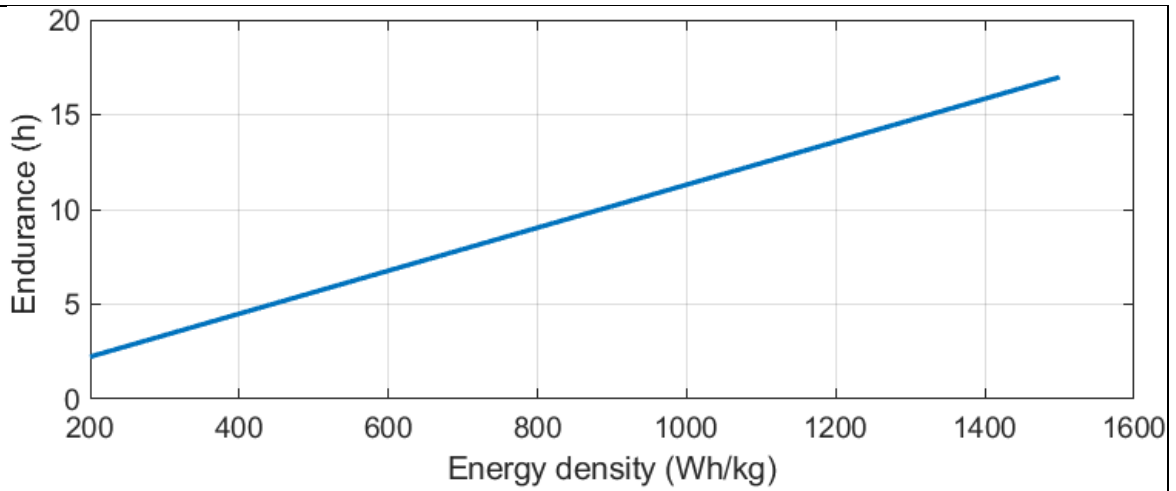
Figure 48. Constrain plot for Hydra UAV powered by PEMFC.

Table 7. Output power constructed from constraining diagram for Hydra UAV.

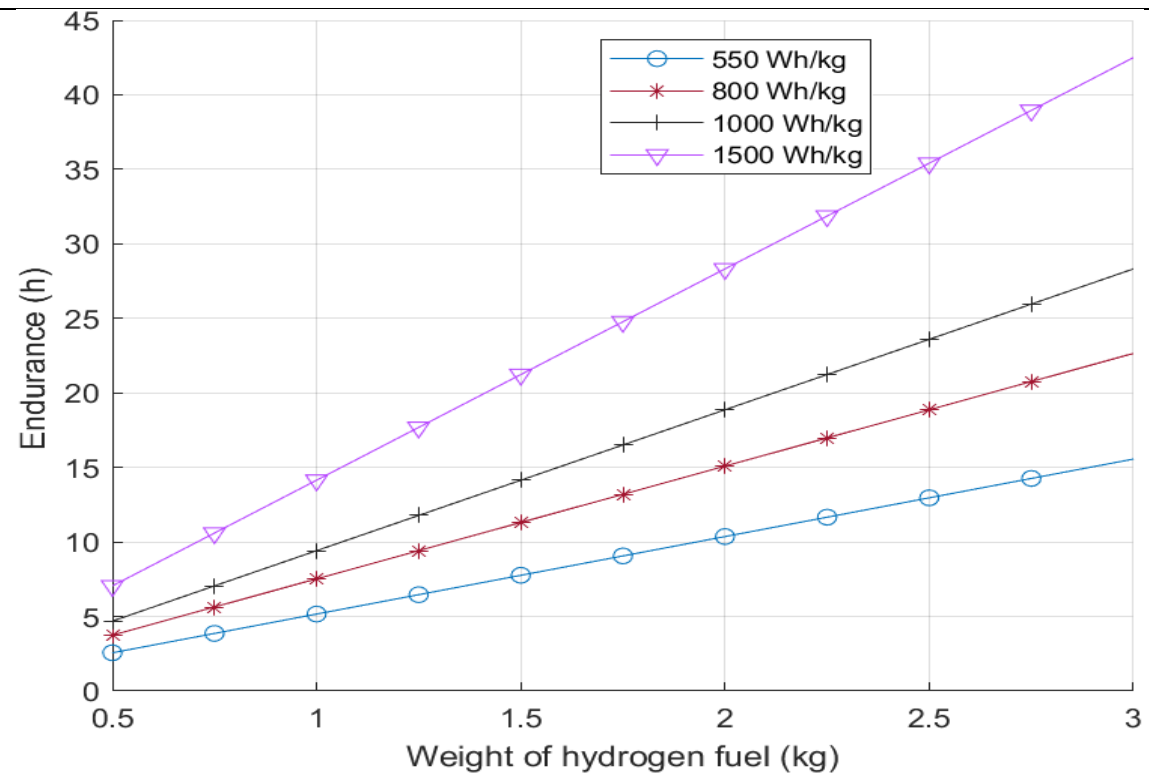
Power (W)	Method proposed	Actual values	Deviation %
$P_{\text{take-off}}$	609	680	- 11.65 %

P_{climb}	373	350	6.57%
P_{cruise}	102	160	-36.25%
P_{vmax}	211	-	
Decent	-	100	
Total power	1295	1290	0.39 %

Using an AEROSTACK fuel cell system with an energy density of 550 Wh/kg, the Hydra aircraft achieved 6 hours of flight time. Based on this study, if a 6.5 kg small UAV using the Aeropak is developed, the endurance of the small UAV will be 1-2 h longer than that of the Hydra. Consequently, the endurance of a small UAV using a PEMFC system can be improved through the conceptual design process. The energy density and the amount of hydrogen fuel in PEM fuel cell UAVs have a large effect on flight endurance. For instance, Figure 49a illustrates the linear relationship between the hydrogen fuel energy density and the endurance of a hydra UAV (6.5kg). The result indicates that by changing the energy density from 550 to 800 Wh/kg, the flight endurance increases 44 %. Figure 49b depicts the effect of the quantity of hydrogen fuel on the endurance for different energy densities. It can be shown that for 2 kg of hydrogen of 1500 Wh/kg, the endurance of the proposed UAV can reach about 30 hours. This is because the hydrogen storage system is a large part of small UAVs for long-endurance missions.



(a)

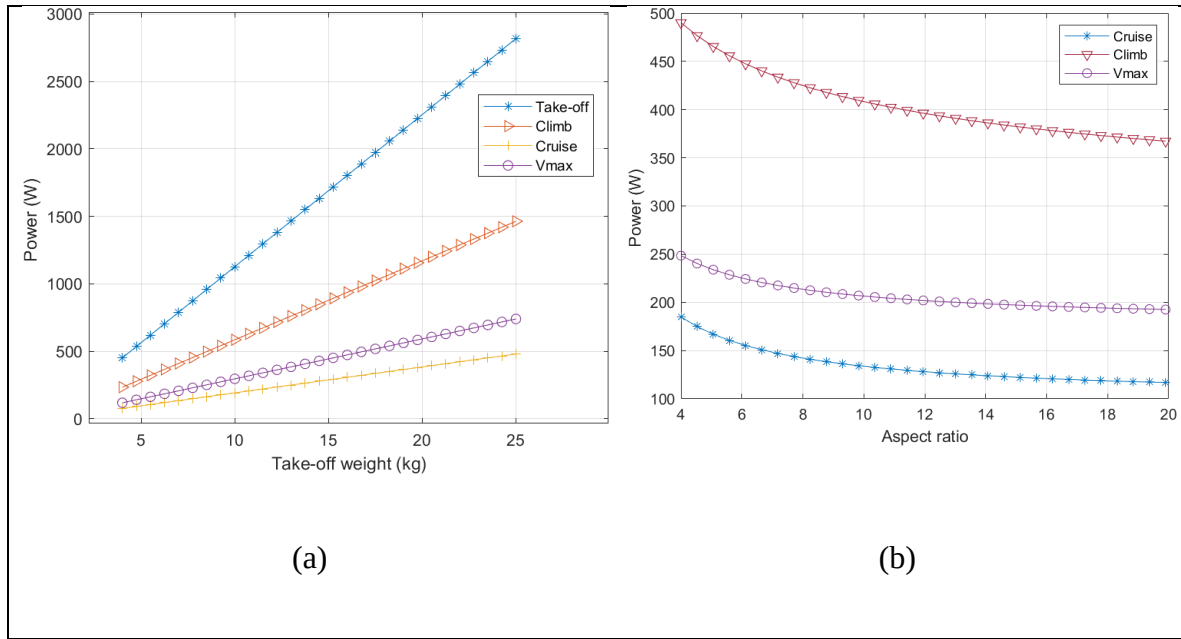


(b)

Figure 49. The effect of a) Energy density and b) Wight of hydrogen, on endurance.

Since the objective of this study is to investigate the propulsion system performance, the output power for different missions is discussed under some input parameters such as take-off weight, aspect ratio, cruise speed, and rate of climb, as indicated in Figure 50 (a-d). Generally, the UAV weight includes the frame, avionic, and propulsion system. For small UAVs, the UAVs' weight can be 4-25 kg. The results indicated in Figure 50a represent the effect of the take-off weight at different missions on the outpower of the propulsion system. Figure 50a indicates a proportional relationship between the take-off and the output power. Additionally, the highest and lowest share of total UAV power is for take-off and cruise flight modes by 47 and 7.8%, respectively. Furthermore, when the UAV's weight decreases, its performance could improve. As a result, by minimizing the weight of the drone, its performance may be improved. However, it is feasible to reduce the weight of the drone to some extent. Figure 50b shows the effect of changing the aspect ratio on the UAV power at different modes. It can be seen from the model equations that the aspect ratio has no effect on the take-off mission. As indicated in Figure 50b, the total power decreases as the aspect ratio increases. For example, when changing the aspect ratio from 8.24 to 13.54, the total power decreases by 4.1 %. At the same time, the climb, cruise, and maximum speed modes decreased by 8.1, 11.5, and 10.1 %, respectively. As a result, most of the influence of aspect ratio changes may be attributed to cruise flying mode. However, the cruising flight phase accounts for the smallest proportion of the total power of the UAV when compared to other flight phases, so the total UAV power is not highly sensitive to aspect ratio variations. As the aspect ratio increases, drag increases, the fly stall becomes closer, power losses decrease, flying endurance and stability enhances, and UAV performance improves. Figure 50c represents the effect of rate climb change on the UAV power at a climb mode. The

change in the rate of climb affects the output power only at the climb mode. At a constant take-off weight (6.5kg), the change in the rate of climb from 3 to 5 m/s can increase the required climb power by 48 %. So, the net power will be highly sensitive to the rate of climb changes. Figure 50d illustrates the effect of cruise speed on the UAV power required for cruise mode. The cruise speed can affect only the power in cruise mode. As it is indicated in Figure 50d, the change in cruise speed from 12 to 15 m/s increases the required cruise power by 34.8 %. This indicates that the total power has lower sensitivity to the cruise speed than to the rate of climb.



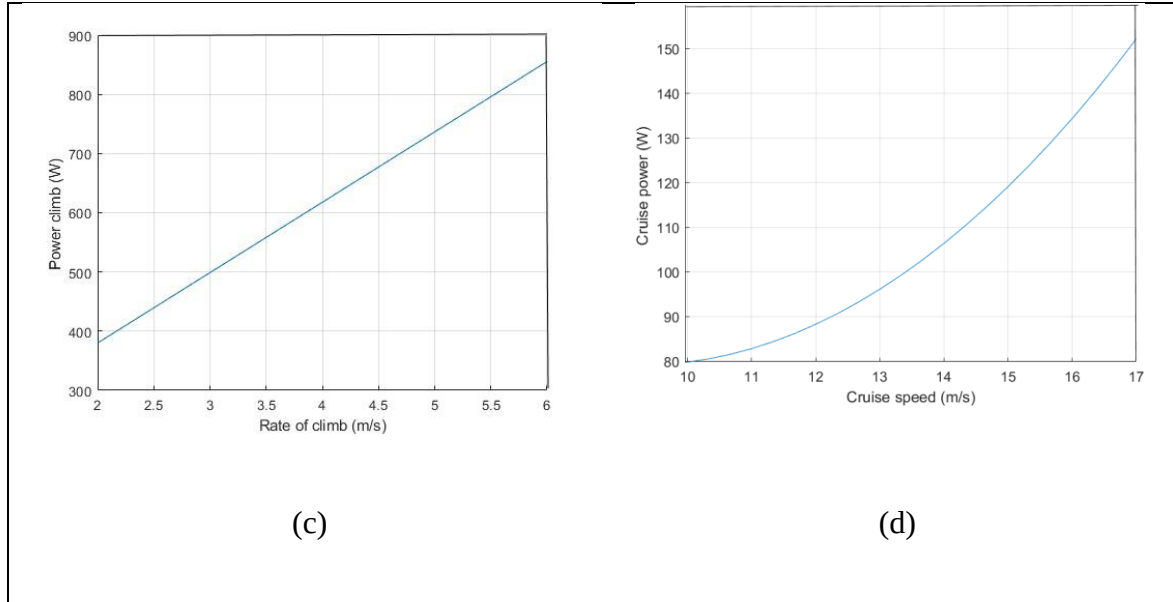


Figure 50. UAV constraint analysis as a function of (a) takeoff weight, (b) aspect ratio, (c) Rate of climb, and (b) cruise speed.

Figure 51a illustrates the relation between the take-off weight of the UAV and its flight endurance. The take-off weight ranges from 4 to 25 kg. When changing the takeoff weight from 4 to 7 and from 10.25 to 15.5 kg, the flight endurance will decrease by 42 and 32.3 %, respectively. Similarly, the increase in the required cruise power will negatively affect flight endurance, as indicated in Figure 51b. For instance, when changing the cruise power from 53 to 110 W and from 211 to 311 W, the flight endurance will decrease by 51.5 and 30.6 %, respectively.

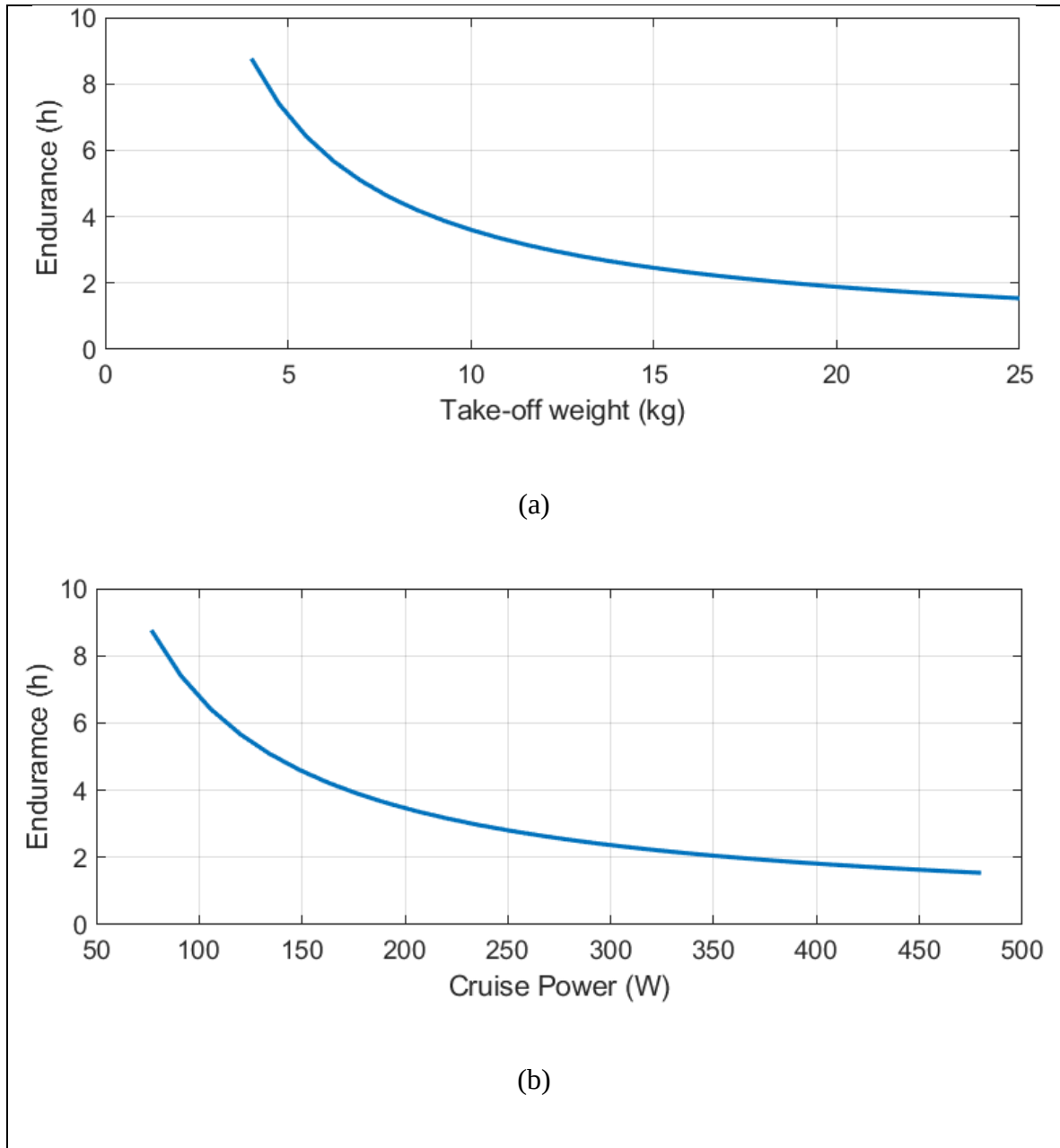


Figure 51. The relationship between flight endurance and a) Maximum take-off weight; b) Cruise power.

The overall results indicate that the proposed UAV requires 1295 W of power to carry out different flight phases. The proposed fuel cell can produce a continuous power of 500 W to operate the propulsion UAV system, and the remaining required power can be obtained from the battery. The battery here can be used when there is a sudden load or during take-off when

the fuel cell needs more start-up time or when the phase requires more power than the fuel cell capacity. Additionally, 1.2 kg of hydrogen is needed to achieve 5-6 hours of endurance (under a hydrogen density of 550 Wh/kg and take-off weight of 6.5 kg).

4.1.4 Optimization of Fuel Cell and UAV Design

Optimization is a complex process since the system response to input variables is hard to predict. To solve this issue, a numerical method has been used. The genetic algorithm (GA) is usually applied to obtain the best solution for engineering problems [227] The multi-optimization approach is centered on improving the outcomes in each generation while keeping the issue limitations in mind. In addition, by optimizing the main variables of the system in the following generation, the optimal outcomes for the objective may be reached [228]. Achieving optimal endurance and the best output power are the main goals of the optimization process in this study. The optimization technique will be done using MATLAB software.

The convergence of the implemented multi-objective genetic algorithm can be easily observed through the plot of cost vs. iterations indicated in Figure 52. The algorithm will eventually converge.

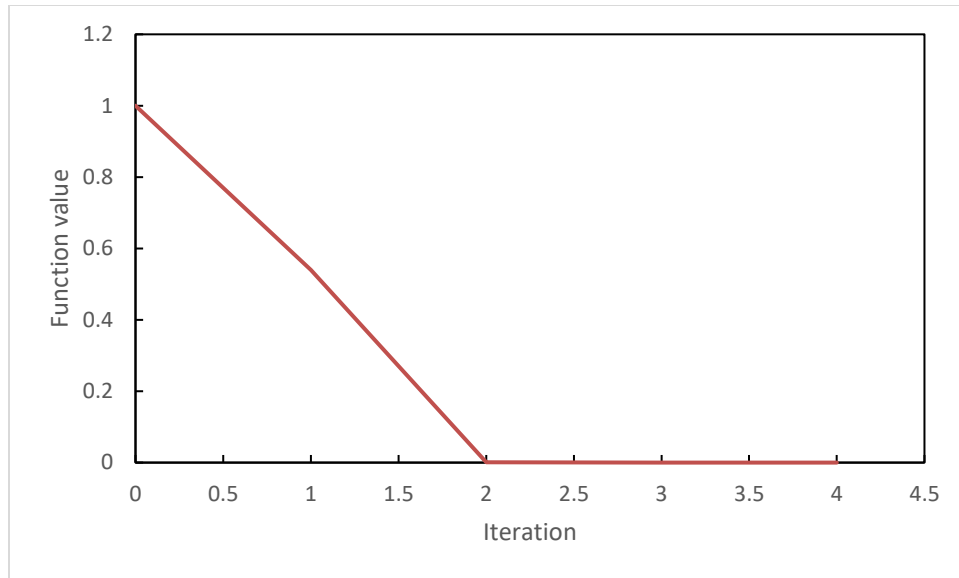


Figure 52. A sample convergence plot.

Additionally, Fitness function is the score to assess the goodness of chromosome to the problem in hand. Through genetic options such crossover and mutation, GA will be able to converge and generate the fittest chromosome that has higher fitness value at the end of GA process. Those main options assure exploitation and exploration; hence Crossover allows exploitation of the good chromosomes generated (parents) and to transfer good genes to offspring from generation to the next and so preserve genetic patrimony. While the mutation assures exploration of search space and assure diversity of the population. Figure 53 assure the convergence of the solution based on the fitness function. Moreover, the pareto front plot is another way of validating the multi objective algorithm convergence, since it is decreasing and converging to infinity as shown in the pareto front plots (Figure 54). In a genetic algorithm, the Pareto front is a set of solutions that represents the trade-offs between multiple conflicting objectives. These solutions are known as Pareto-optimal solutions, because they are not dominated by any other solution in the set. In other words, it is not possible to improve

one objective without degrading one or more of the other objectives. Convergence to the Pareto front occurs when the genetic algorithm can find a set of solutions that are close to the true Pareto front. This can be challenging, because the Pareto front is often complex and may have many local optima. To converge to the Pareto front, the genetic algorithm must be able to effectively explore the search space and find a diverse set of solutions that are not dominated by any other solutions. This requires the use of appropriate selection and crossover operators, as well as good parameterization of the algorithm. Once the genetic algorithm has converged to the Pareto front, it can be used to identify the best trade-off solutions for a given problem. This can be useful in decision-making, where multiple conflicting objectives need to be considered.

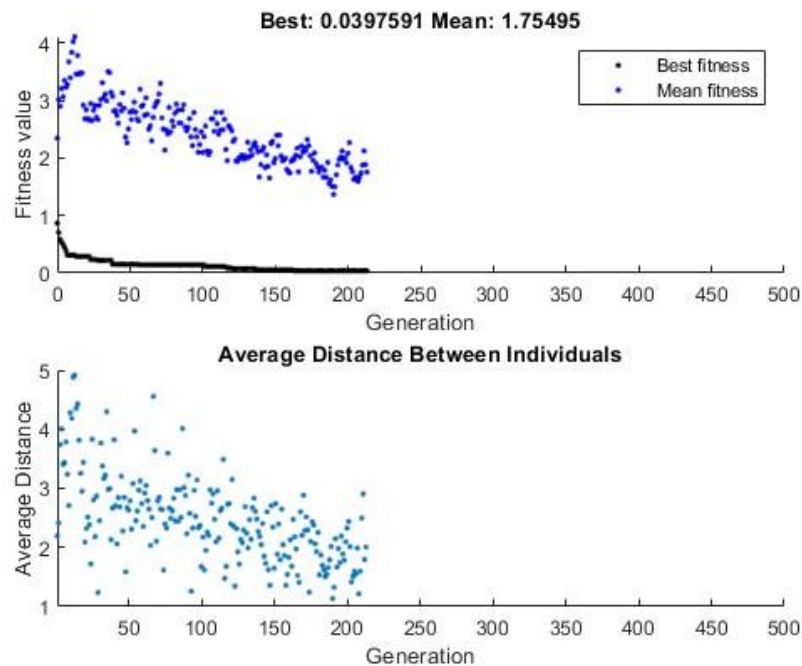


Figure 53. Setting the Crossover Fraction.

A multi-objective optimization based on a genetic algorithm is represented to achieve optimal performance for a UAV powered by fuel cell which is proposed in the previous section. The optimization objective is to simultaneously maximize the UAV flight endurance and minimize its total required power (to drive UAV at different flight phases). The design variables are Take-off weight, aspect ratio, rate of climb, cruise speed, the energy density of the fuel (mainly hydrogen fuel), and the weight of the hydrogen fuel. The upper and lower bounds of design variables are indicated in Table 8. The UAV take-off weight and payload are fixed (6.5 kg).

Table 8. Preliminary upper and lower boundaries for input design parameters.

Design Variable	Upper bound	Lower bound
Aspect ratio AR	4	20
Cruise speed V_{cr} (m/s)	7	17
Rate of climb RC (m/s)	3	6
Energy density of fuel ED_h (Wh/kg)	240	1500
Weight of hydrogen fuel (kg)	1.2	3

To assess the optimal solutions of UAV in different design variables, the UAV model mentioned in the previous section is now deployed in a multi-objective optimization

algorithm. Pareto front approach has been widely used in multi-objective problems. Pareto optimal solutions are obtained for six design variables, as depicted in Figure 54. The Pareto front approach is accomplished using a population size of 300. The corresponding Pareto front of two objectives totally required power, and total flight endurance has been represented in Figure 54. It is clear from this figure that choosing a value for one objective could cause a worse value for another objective. Fortunately, this will serve our objectives since one objective needs to be minimized, and the other one needs to be maximized. Three optimum design points were chosen, at the top left of figures for four different take-off weights. As shown in the Pareto front diagrams, the optimum point for 6.5 kg UAV has the maximum endurance and the minimum total power of 20.07h and 1084.8W (see Figure 54a). For 10 kg UAV (Figure 54b), the endurance decreases by about 6.69 hours, and the total missions power increases by 584.9 W compared to the 6.5 kg weight. For UAV with 15 kg shown in Figure 54c, the performance is still good, and the longest endurance is 8.65 hours and 2504 W of total power. Moreover, Figure 54d shows that the UAV with 20 kg take-off weight achieves optimal endurance of 6.4 hours and a total power of 3343 W. It can be noticed that the increase in the takeoff weight will reduce the flight endurance and require more power.

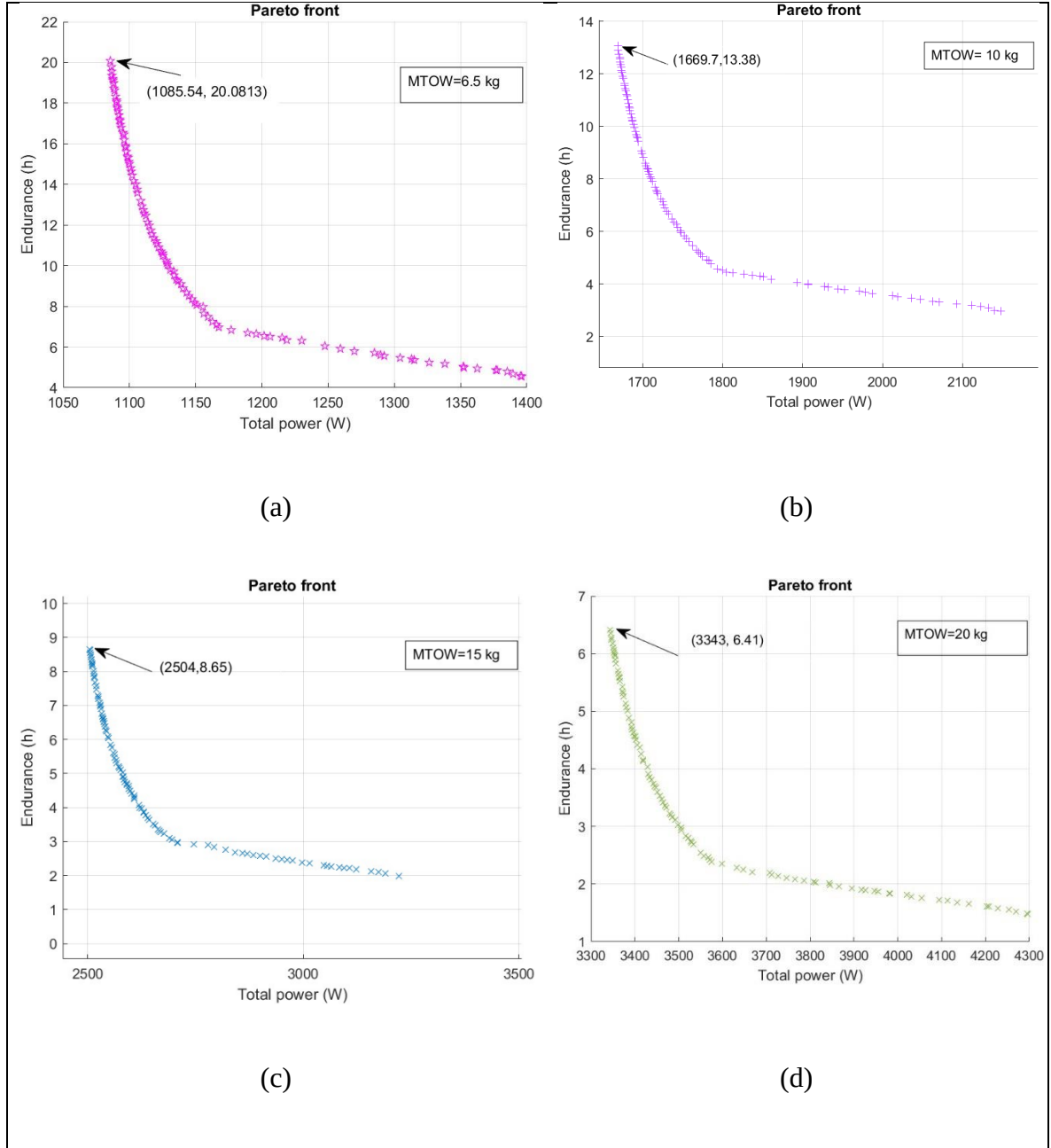


Figure 54. Pareto optimal solutions plot for the designed variables, and objective output.

Table 9 shows the design variables' parameter values for the above four takeoff weights. As indicated in Table 9, the high aspect ratio achieves better performance; for all different UAV weights, the aspect ratio is close to 20 which is the maximum limit used for the optimization. For the cruise velocity, the smaller cruise velocity enhances the performance better than the

higher cruise speed. In the case of the other design variables, we can notice that, for the three points, the values of the rate of climb, energy density, and hydrogen fuel mass are close to each other, and they are about 2 m/s, close to 550 Wh/kg and close to 2 kg respectively.

Table 9. Chosen design variables and objective functions outputs.

	Designed input variables					Optimal solution	
UAV weight	Aspect ratio	Cruise speed [m/s]	Rate of climb [m/s]	Energy density [Wh/kg]	Hydrogen mass [kg]	Total required power [W]	Endurance [hours]
6.5 kg	19.97	8.1	2	556.57	1.97	1084.8	20.07
10 kg	19.85	7.87	2	572.4	2.43	1669.7	13.38
15 kg	19.97	7.95	2	553.32	1.69	2504	8.65
20 kg	19.67	8.53	2	558.15	1.73	3343	6.41

4.2 Battery Model Analysis

In this section, a battery model is validated, and a case study of Staaker BG-200 UAV (26-inch coax 8-rotor) is discussed. General analysis includes the effect of MTOW and endurance and power on the UAV performance.

4.2.1 Battery Model Validation

A validation test against the experimental results of battery actual capacity is shown in Figure 55. The analytical model mentioned in section 3.3 shows a good agreement with the experimental data done in ref [211]. This means that the battery model can be reliable to be

used and applied into the UAV propulsion system. This model is considered in battery model through the introduction of a battery available capacity factor, k_B . This is characterized by considering the minimum battery capacity during its lifetime to be 80% [211].

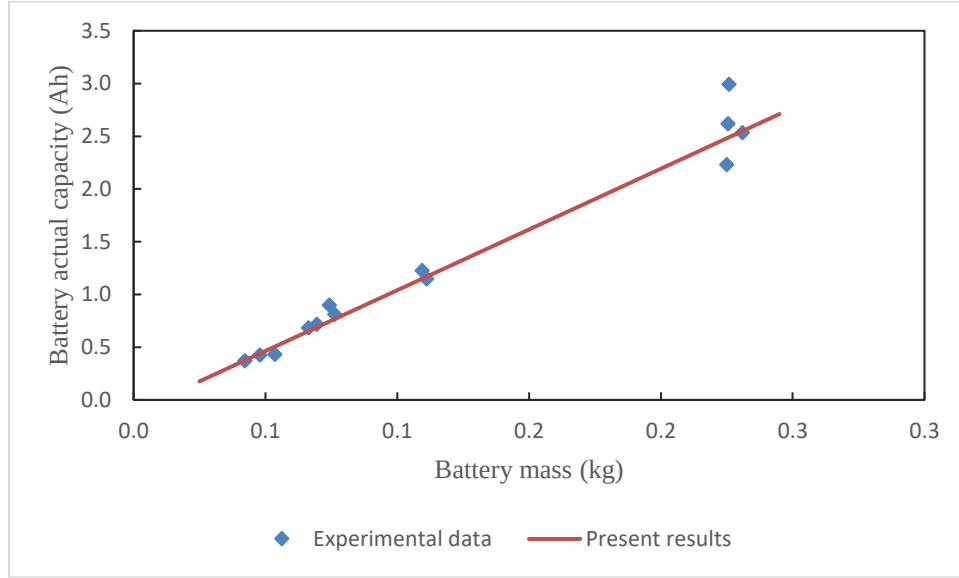


Figure 55. Validation of Battery mass vs battery actual capacity data from [211].

4.2.2 Battery Model Integrated with Rotary UAV

The parameters of the Staaker BG-200 UAV (26-inch coax 8-rotor) were used to show the impact of increasing the take-off weight of the UAV. Figure 56a depicts the changes in flight endurance with take-off weight while all else remains constant. At a maximum take-off weight of 25 kg, the endurance is projected to be 33 minutes and 44 seconds, assuming constant propulsion efficiency. This is 44% less than the 60-minute reference endurance. Figure 56b depicts the approximated variation in endurance due to the mass reduction. A one Kg weight reduction in the reference UAV results in an estimated endurance improvement of 5 minutes and 42 seconds.

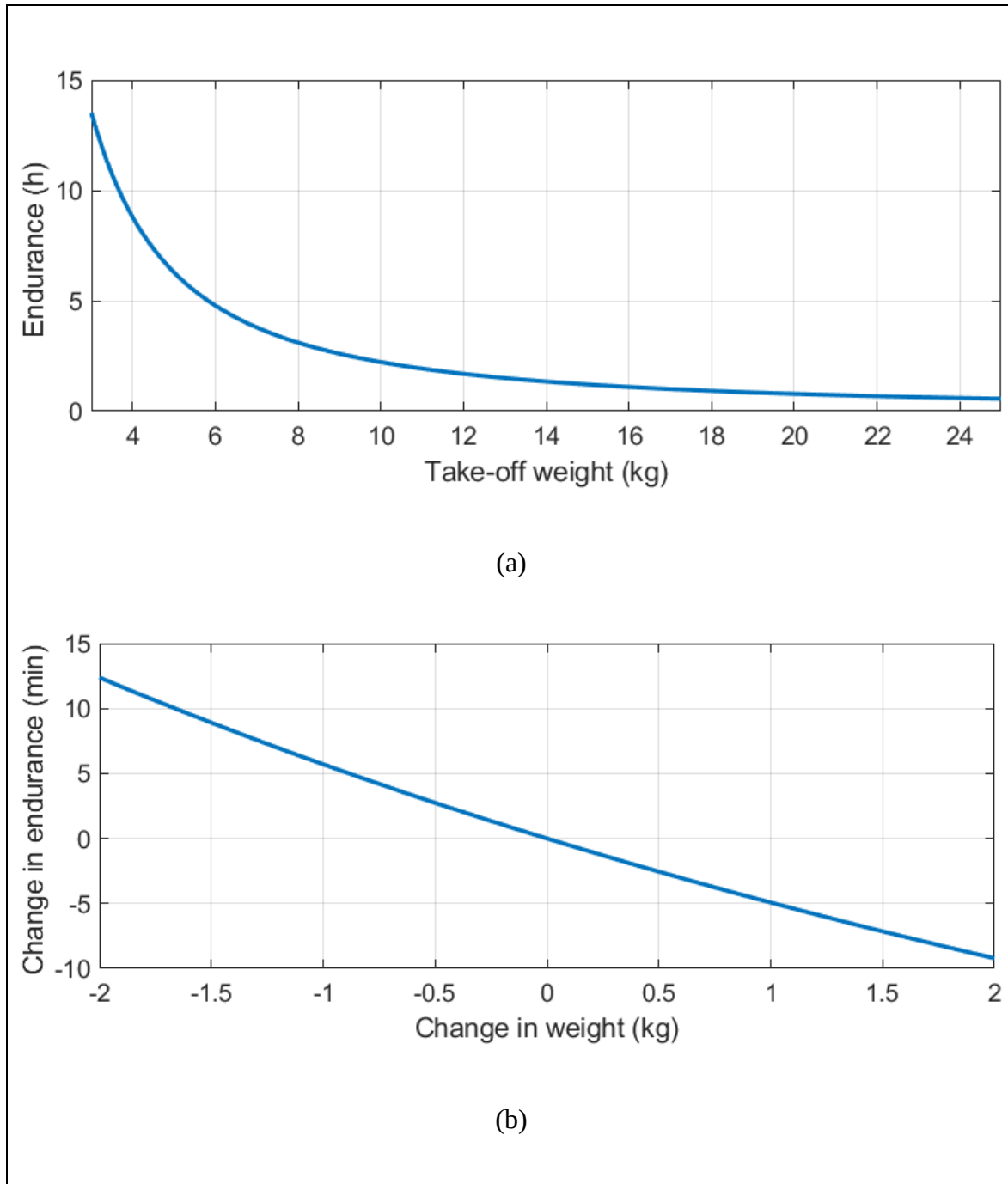
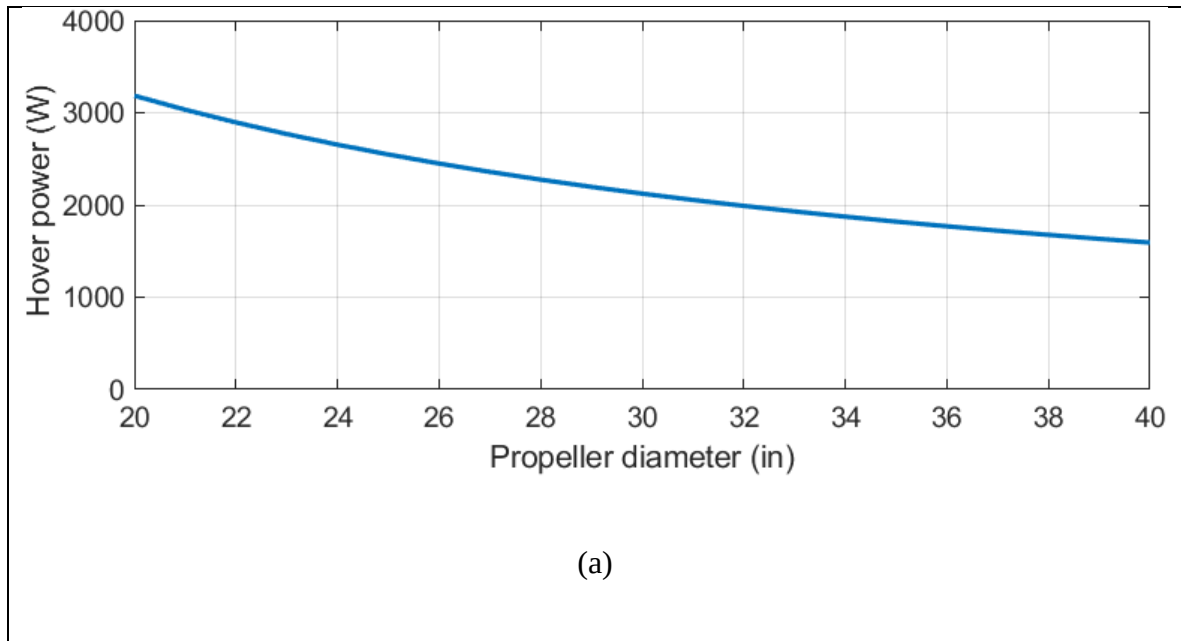


Figure 56. The effect of a) Take-off weight, and b) change in weight on estimated endurance.

Figure 57a illustrates the effect of propeller size on the required hover power of the UAV. The diameter of the propeller was adjusted from 20 to 40 inches while keeping everything else unchanged. The weight was set at the MTOW of 25 kg, and else Staaker BG-200

parameters were utilized. The power consumption for the same thrust was cut in half when the diameter increased. Figure 57b demonstrates the effect of propeller size on the estimated endurance for two configurations (coaxial 8-rotor and in-plane 8-rotor). In general, the flight time increases with the increase of the propeller diameter. When controlling the configuration of being in a plane or coaxial, the flight endurance increases due to the number of rotors. The in-plane configuration achieves higher estimated endurance of 83 minutes.



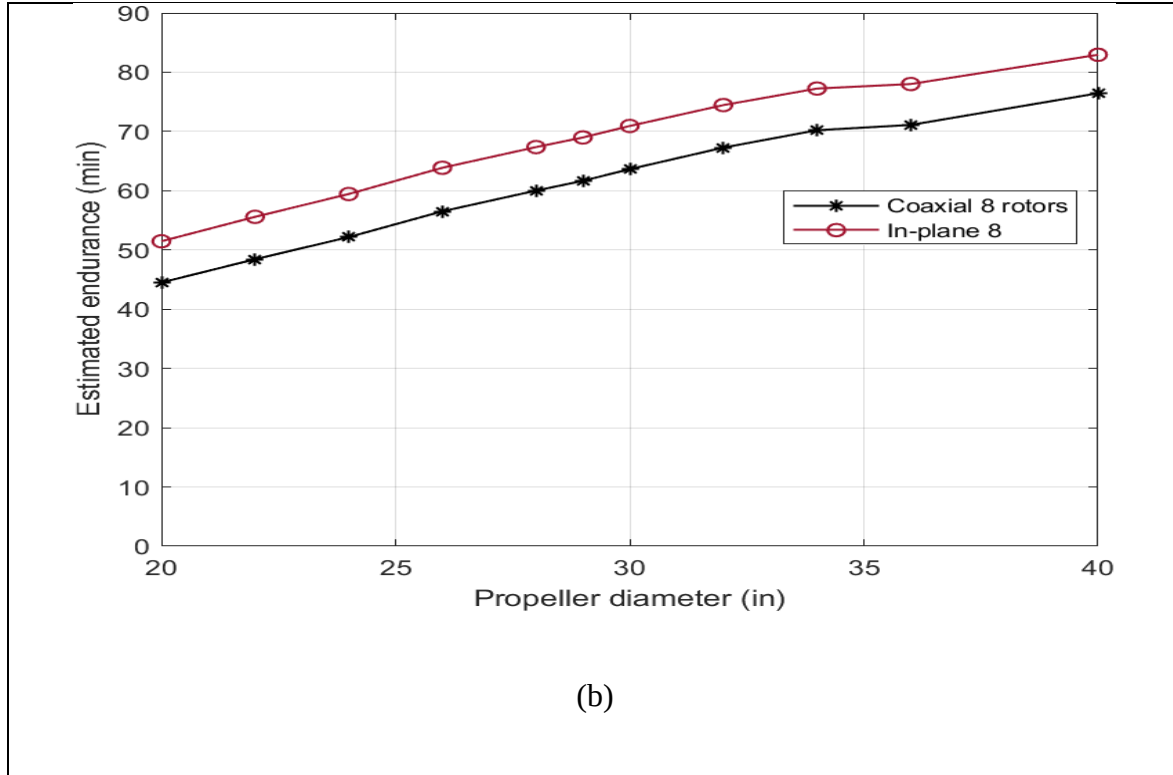


Figure 57. The effect of propeller size on a) hover power, b) endurance.

When the number of blades and propeller size were controlled, coaxial rotor designs had lower endurance predictions than in-plane rotor arrangements. This was predicted due to the efficiency loss that happens when the top and bottom propellers come into contact with coaxial rotors. The bulk of the arms utilized in coaxial designs is reduced since they are half the length and half the number. This drop in bulk was insufficient to compensate for the efficiency loss.

4.3 PV Model Analysis

In this section, the PV model is validated and analyzed for different four locations inside KSA, including Dhahran, Riyadh, Jeddah and Abha. The solar irradiance and solar power necessary to drive the UAVs are discussed. Finally, the solar cell model UAV is flying for 7.1 hours during daytime only.

4.3.1 PV Model validation

The PV model is validated against based on the I-V plot against the manufacture data mentioned in Table 6. The validation test represented in Figure 58 shows a great agreement between analytical model results and the real data from the manufacture which makes the mathematical model mentioned in section 3.4 PV Model reliable to use. The validation done here is for a maximum sun irradiance of 1 kw/m^2 and a temperature of 25°C .

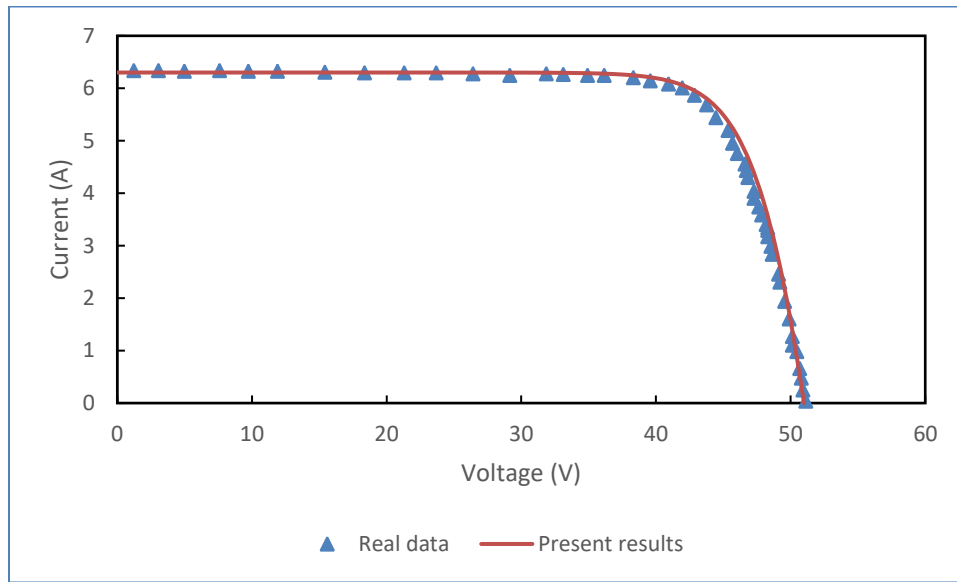


Figure 58. PV model validation at 1 kw/m^2 and 25°C , aagainst manufacturer data [229].

4.3.2 PV Model Results and analysis

The generalized PV model performance is shown in Figure 59 and Figure 60. The simulated PV cell specifications are mentioned in Table 6. Both I-V and P-V outputs are analyzed under different cell temperatures and different solar intensities. Figure 59 illustrates the performance curves of both I-V and P-V under a light intensity of 1000 W/m^2 and solar cell temperatures of 25°C , 35°C , 45°C , 55°C , and 65°C . The I-V curves in Figure 59 (a) indicate that when the temperature of the solar cell increases, the output voltage decreases while the light intensity remains constant, but the temperature increase has minimal effect on the output

current, which remains around 6.3 A. Similarly, the maximum output PV power decreases with the increase in the temperature under constant sun intensity; hence, its corresponding output voltage decreases due to temperature rises (Figure 59b). For instance, the maximum power at a cell temperature of 25 °C is 255W and about 221.5W at 65 °C.

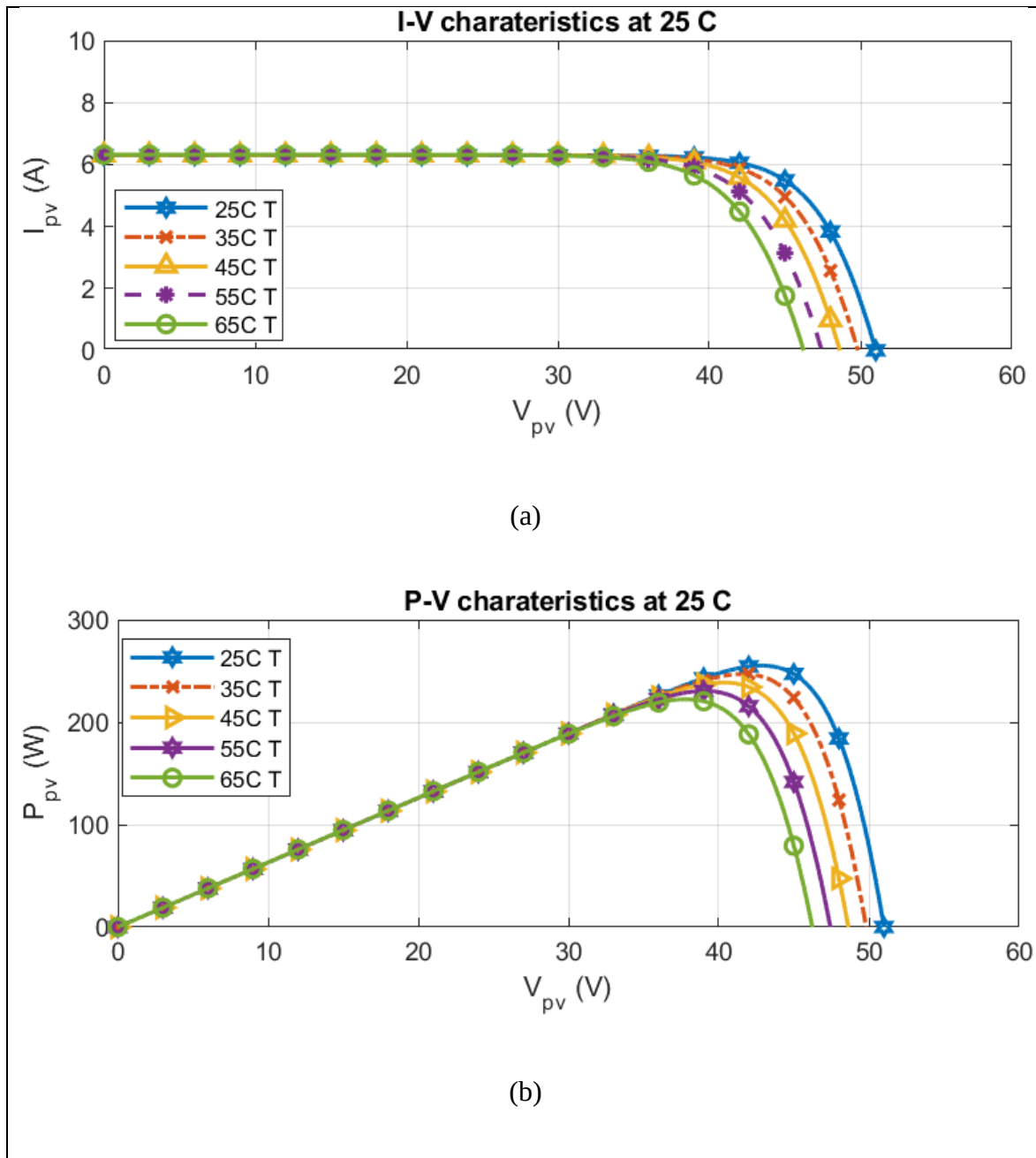
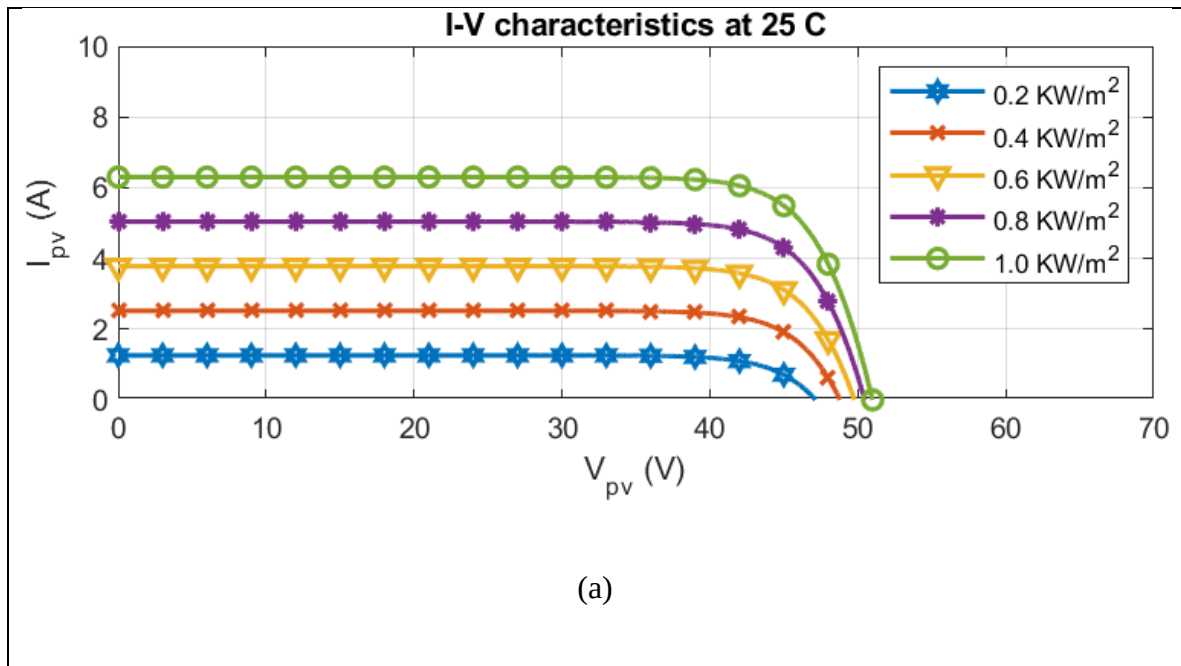


Figure 59. The I-V and P-V curves of solar PV under different cell temperatures; (a) I-V curve and (b) P-V curve.

The effect of varying solar intensity under constant cell temperature (25 °C) is shown in Figure 60. Figure 60a indicates that the variation in light intensity has made a significant impact on the output current of the solar cell. When the sun intensity goes from 0.2 kW/m² to 1kW/m² the open circuit solar cell current increases from 1.3 to 6.3 A, respectively. The amount of light has minimal influence on the solar cell's open circuit potential. With increasing light intensity, the output voltage of the solar cell rises a little. Figure 60b shows a significant impact on the PV cell output power due to the amount of sun intensity. The output power of the solar cells increases as the solar intensity increases from 0.2 KW/m² to 1 KW/m². The maximum output power has grown as the output voltage of the solar cell has increased. However, after the maximum power value is achieved, the output power decreases as the output voltage increases.



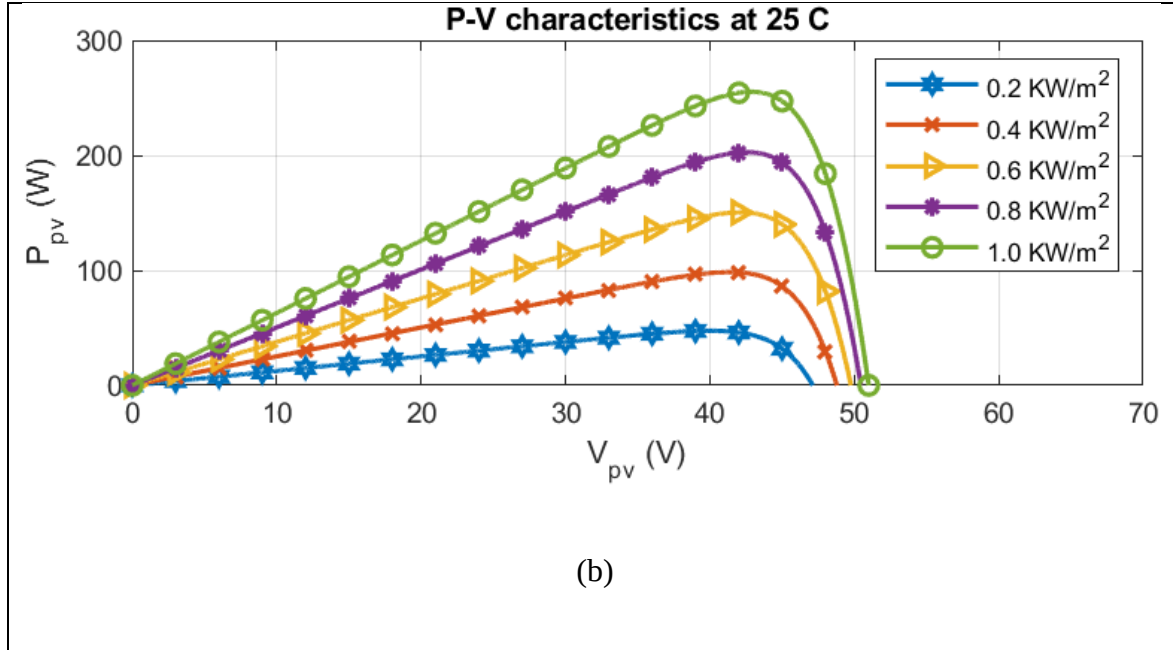


Figure 60. The I-V and P-V curves of solar PV under different solar intensity values: (a) I-V curve and (b) P-V curve.

Figure 59 and Figure 60 analysis indicated that the output power of the solar cell is directly connected to the intensity of the sunlight and the solar cell temperature, and the output power of the PV panels fluctuates with the cell temperature and the lighting intensity. As a result, we must use the appropriate control method for solar UAVs in order to manage the output power and accomplish the efficient conversion of solar energy and photovoltaic cells.

The Kingdom of Saudi Arabia has considerable potential for solar energy due to the considerable solar irradiance compared to other countries. Since Saudi Arabia has different climate and weather conditions, the use of solar energy in these regions can be attractive. In this study, four different cities were chosen to study the PV characteristics. These regions are Dhahran, Riyadh, Jeddah, and Abha. The geographical and climate characteristics of these four cities are mentioned in Table 10. Additionally, the average high and low temperatures are represented in Figure 61 for these four cities.

Table 10. Geographic and climate characteristics for different zones [230,231].

Zone	Latitude (°)	Longitude (°)	Altitude (m)
Dhahran	26.236355	50.032600	44
Riyadh	24.4115	46.4318	612
Jeddah	21.543333	39.172777	49
Abha	18.2465	42.54117	2200

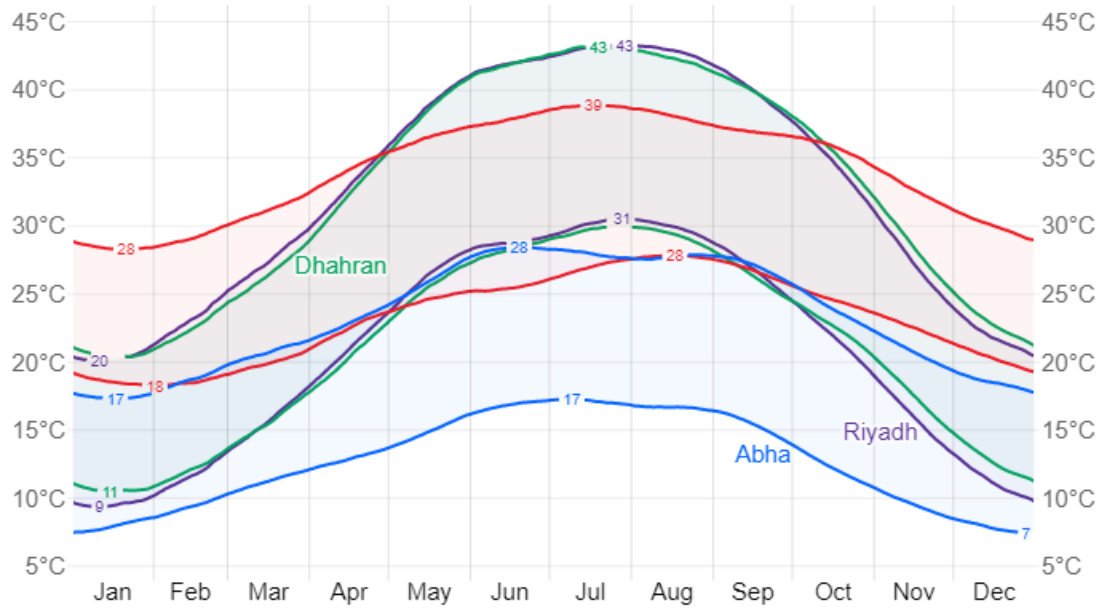


Figure 61. Average high and low Temperature temperatures in Riyadh, Dhahran, Jeddah, and Abha [232].

Figure 62 shows the average monthly solar insolation for different climate zones. The data in Figure 62 are obtained from the fact that the solar cell panel is oriented south. The PV

analysis performance will be investigated for these four cities. For this aim, the solar PV's I-V and P-V curves for June and November are examined in Figure 63 and Figure 64. According to Figure 62, in June, the average solar insolation for Dhahran, Riyadh, Jeddah, and Abha was 7.75, 7.87, 6.965, and 6.91 KWh/m²/day, respectively. Also, in November, the average solar insolation for Dhahran, Riyadh, Jeddah, and Abha are 4, 4.22, 4.639, and 4.96 KWh/m²/day, respectively.

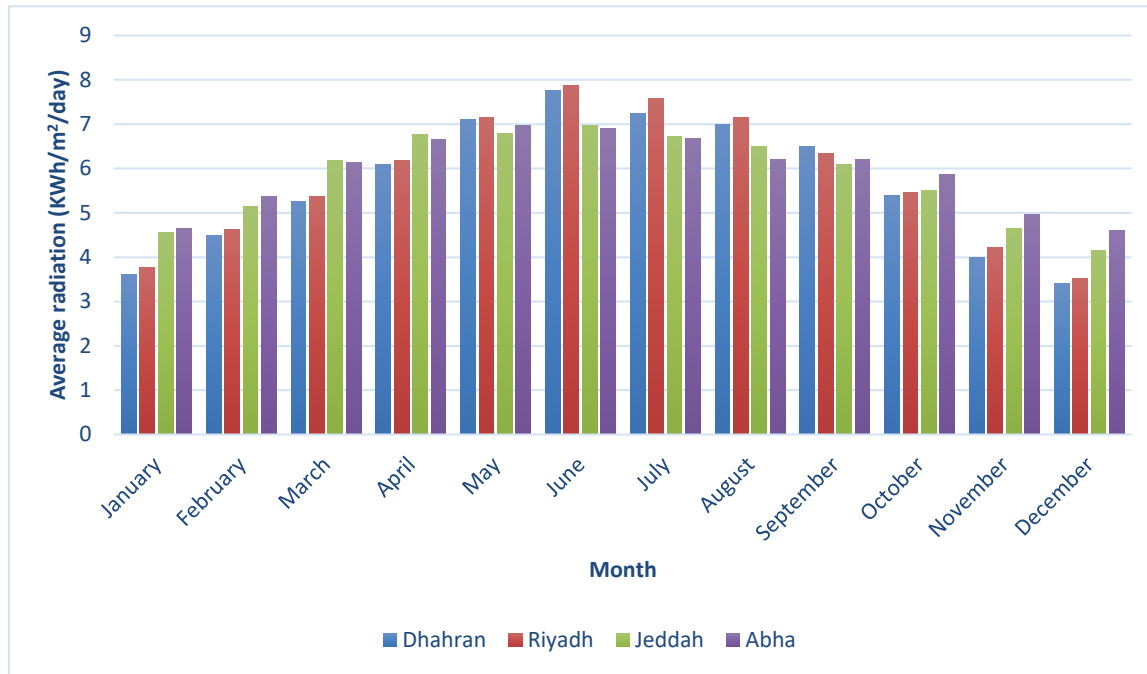


Figure 62. Average solar insolation for different zones in KSA [233–236].

Figure 63 indicates that for June, the highest and lowest current and power produced by the PV panels are for Riyadh and Abha, with a maximum output power of 198.8W and 174.2W, respectively. However, for November (Figure 64), the highest and lowest PV cells' output current, and power are for Abha and Dhahran, with a maximum output power of 123.33 W and 98.45 W, respectively. The explanation for this is because, in November, unlike June,

solar irradiance in Abha (4.96 KWh/m²/day) is higher than in Dharan (4 KWh/m²/day) and Riyadh (4.22 KWh/m²/day).

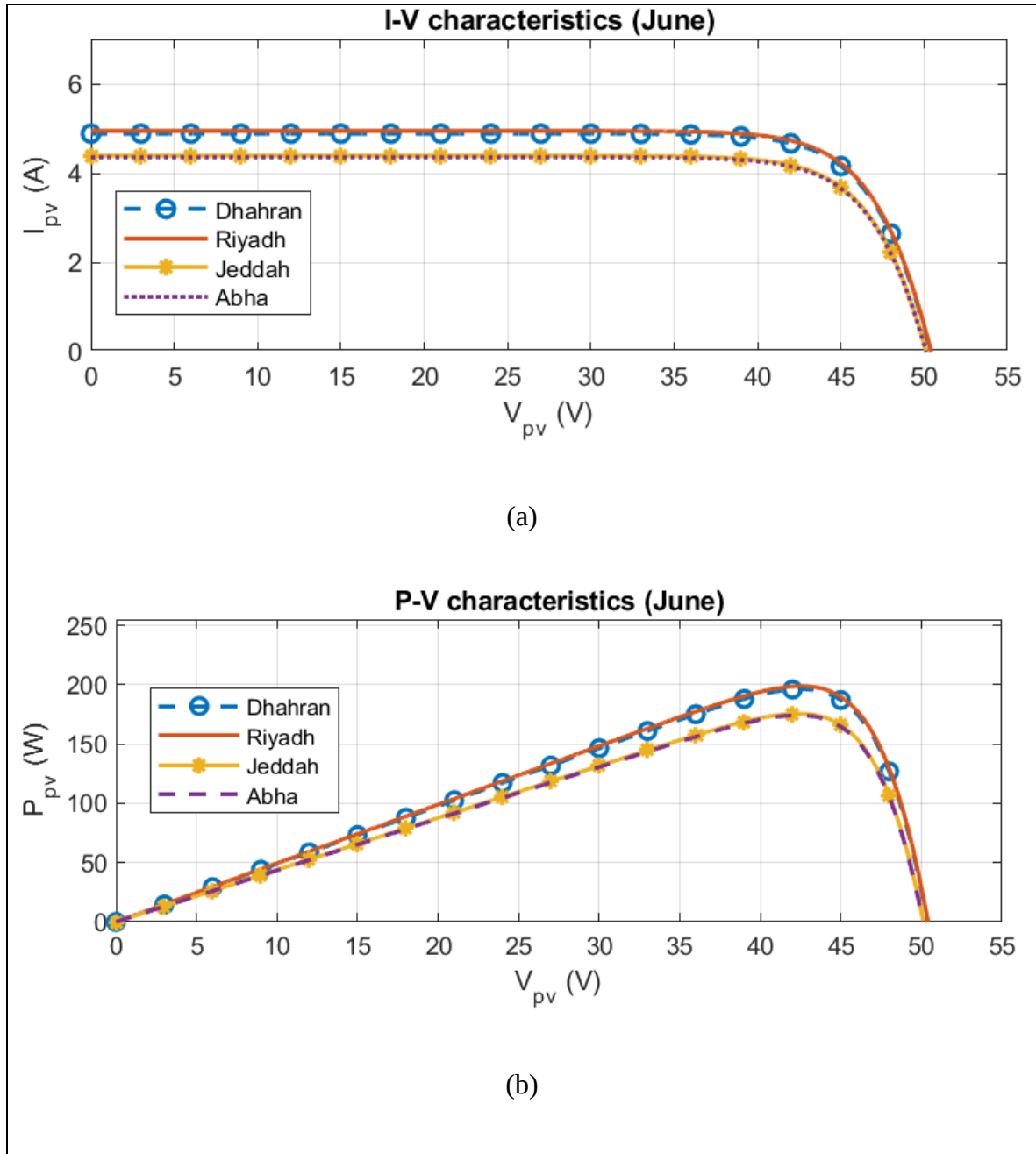


Figure 63. The I-V and P-V curves of the solar PV in the different climatic zones; (a) I-V curves in June and (b) P-V curves in June.

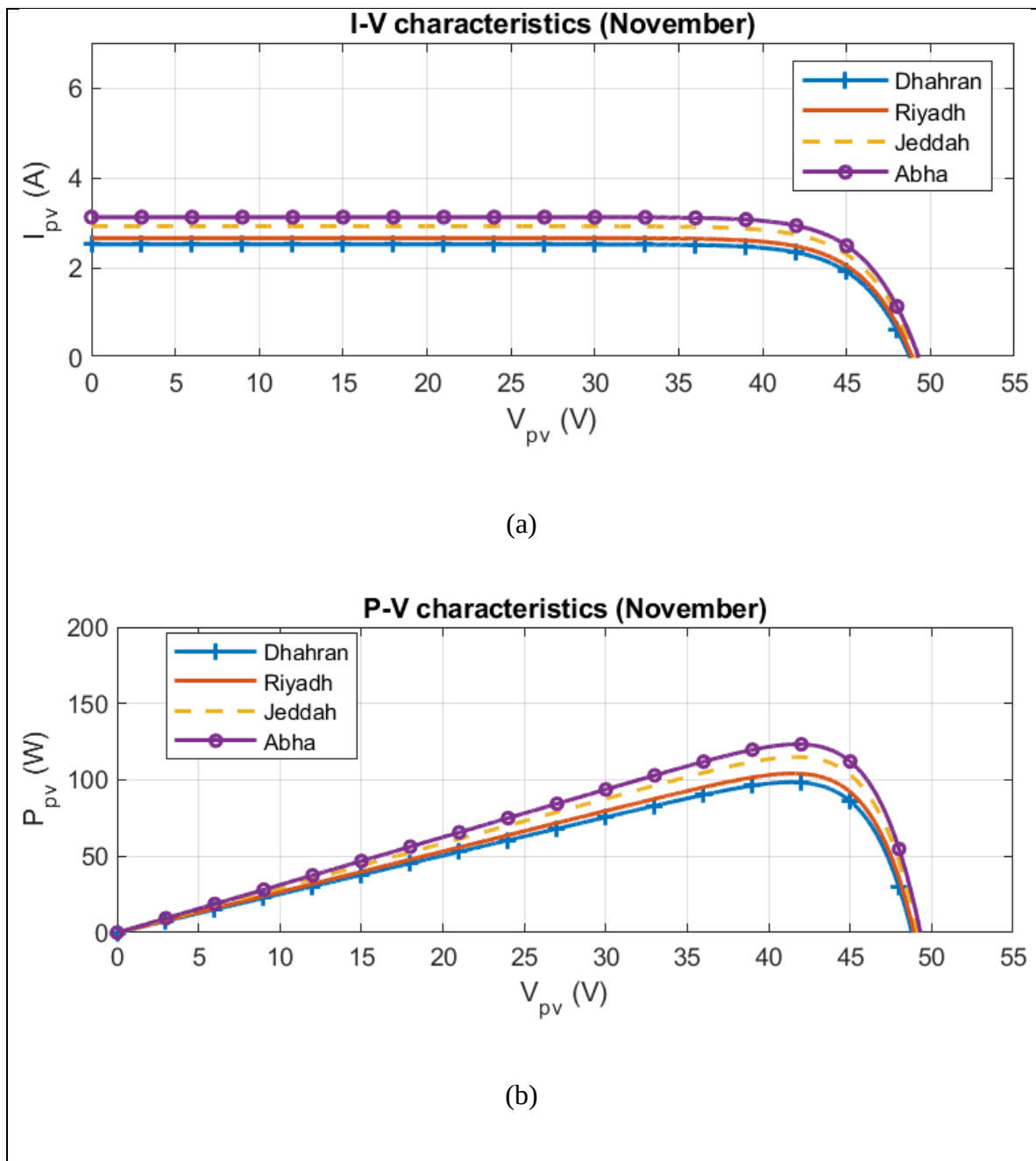


Figure 64. I–V and P–V curves of the solar PV in the different climatic zones; (a) I–V curves in November and (b) P–V curves in November.

4.3.3 Solar Cell Model UAV Flying Only at Daytime

The solar UAV model can be used to design an airplane that flies only during daytime. This means there is no need for the battery and the night-time will be assumed to be zero. Elimination of the battery means the solar area will be lower, which is logical as no battery needs to be charged during the flight. Table 11 shows the design parameters for mini solar UAV based on in ref [222].

Table 11. mission parameters of a very small UAV.

Parameter	Value
Payload mass m_{pld} (kg)	0.01
Payload power consumption P_{pld}	0
Day length T_{day} (h)	13.2
Altitude (m)	500
Aspect ratio AR	10
Wingspan b (m)	0.5
Total mass (kg)	0.300

The results presented in Figure 65 show the UAV solar power during the daytime and the total electric power required to operate the UAV. Figure 65 shows maximum solar power of 26.96 W, obtained from the solar cells, while the total required power is shown to be 17.67 W. At the beginning of sunset, the solar power is not sufficient to fly the UAV, after 2.5 hours from sunset, the solar cells can deliver more than the required electric power for 7.18 hours, and then the solar power delivered becomes less than the required power, which end the journey of the UAV.

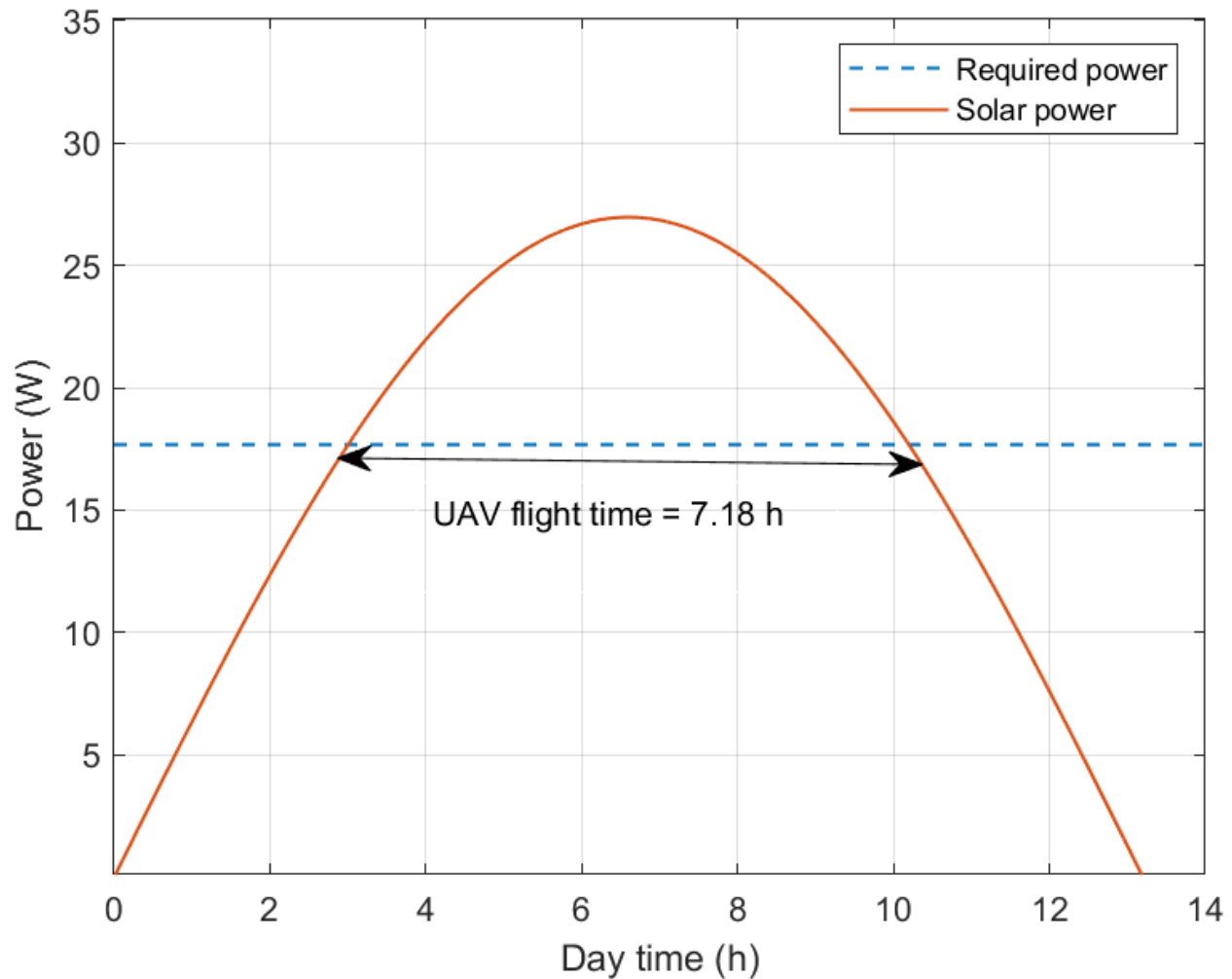


Figure 65. Solar power during daytime.

Figure 66 demonstrate that the smallest UAV wingspan is roughly 30 cm for speeds ranging from 6 to 8 m/s. A mini airplane is commonly described as having a span of less than 15.24 cm and a weight less than 100 g, thus even if you choose the solutions with 30 cm, it is not considered as a mini airplane. It is not advisable to choose the designed variables near the limit of the solution domain since a minor modification in one of these variables, such as a heavier structure, might lead the mini airplane to fail to achieve the objective (Figure 66a). Furthermore, an aircraft with a very low aspect ratio has more flexible dynamics around the roll axis than an airplane with a high aspect ratio. Taking this into consideration,

and with low speed as a selection criterion, an airplane with a wingspan of 0.8 m and an aspect ratio of 10 would be the optimum solution. in general, as indicated in Figure 66, increasing the wingspan will cause an increase in the UAV mass, speed, total power and wing area, on the other hand, the increase in aspect ratio will lead to less mass, speed, total power and wing area.

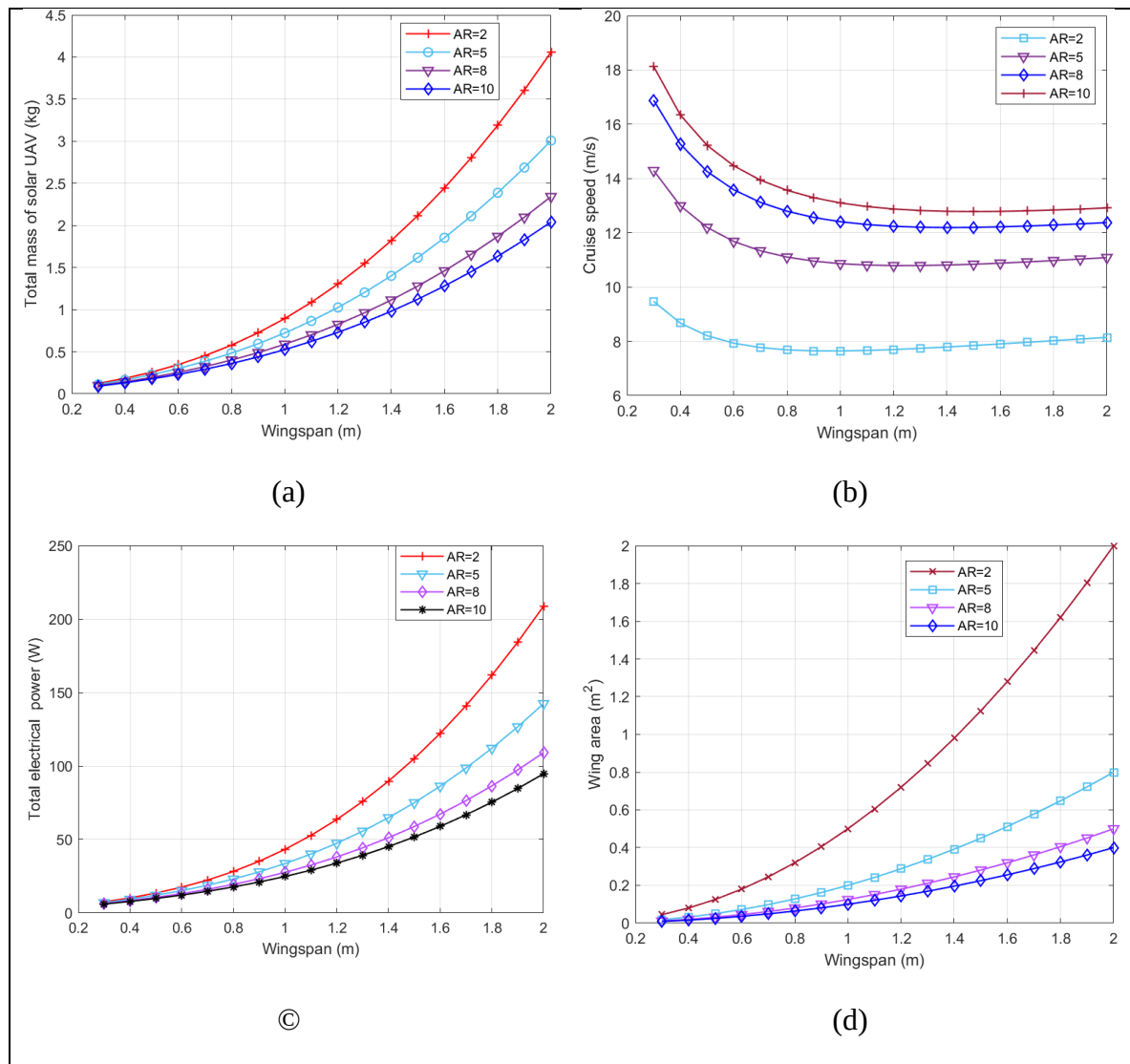


Figure 66. UAV flight Characteristics based on wingspan and aspect ratio.

4.4 Hybrid Model Analysis

In this section, a hybrid system of solar cell and batteries is discussed for continues flight of 24 hours. In addition, a full hybrid of solar / fuel cell and batteries is introduced for small and large UAVs. The optimization process is done for both systems to indicate the optimal design variable and the optimal power and endurance outputs.

4.4.1 Hybrid SC + battery Flying 24 Hours

In this section, we will investigate the mission and design variables for a 2.5 kg UAV 9Sky-Sailor) flying 24 hours. Various airplane wingspan and aspect ratio are analyzed. Furthermore, for different design variables, an optimization process is carried out for different small UAV weights.

Table 12. Mission parameters of Sky-Sailor model UAV.

Parameter	Value
Payload mass m_{pld} (kg)	0.05
Payload power consumption P_{pld}	0.5
Day length T_{day} (h)	13.2
Altitude (m)	500
Aspect ratio AR	12.9
Wingspan b (m)	3.2
Total mass (kg)	2.6

Figure 67a indicates that the minimum wingspan for the UAV required for flying 24 hours continuously is 2.2 m. also, the maximum limit for wingspan is 5.2 m, indicating that continuous flight is no longer possible with wingspan bigger than about 4.5 m. This is because the aircraft gets too heavy over a certain wingspan, making it impossible to fly

continuously with the power supply. Going higher in size would necessitate a reduced airframe weight model. The maximum cruise speed can be ranged from 12 to 13 m/s for aspect ratio 20 and higher wingspan, similarly, the lower the aspect ratio and wingspan, the lower is the cruise speed of UAV (Figure 67 b). similarly, the total electric power increases due to the increase of both wingspan and aspect ratio as shown in Figure 67c. The UAV wing area is increasing due to the increase in the wingspan and the decrease in the aspect ratio (see Figure 67d).

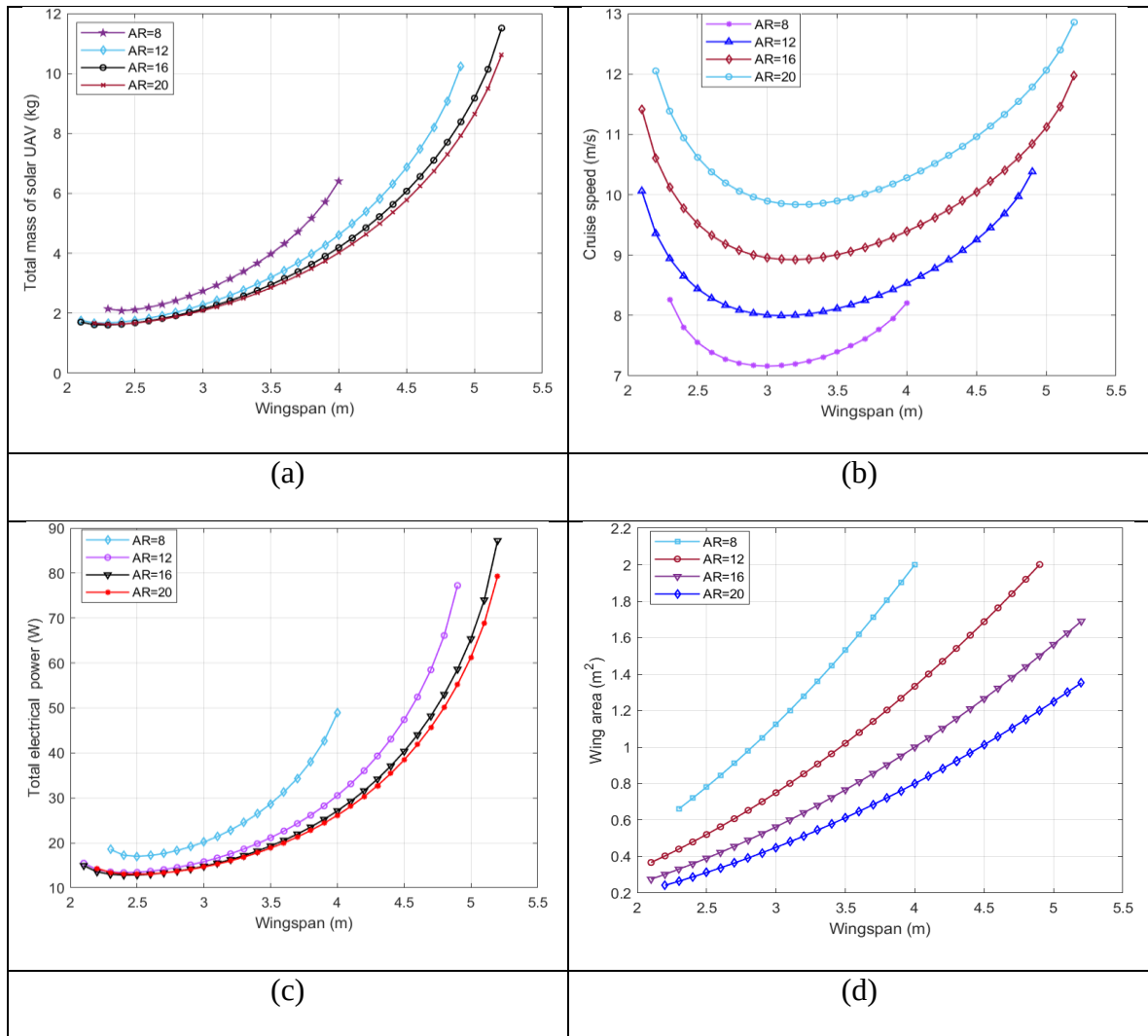


Figure 67. UAV flight characteristics in terms of wingspan and aspect ratio.

After investigating the small UAV model under different wingspan and aspect ratio, the optimization process is performed to test several input design variables including aspect ratio, wingspan, battery energy density, and flight altitude. The initial upper and lower limits for these design variables are indicated in Table 13.

Table 13. Preliminary upper and lower boundaries for input design parameters.

Design Variable	Upper bound	Lower bound
Wingspan b (m)	2.5	5
Aspect ratio AR	10	20
Energy density of battery (Wh/kg)	190	240
Altitude (m)	500	30000

The objective function here is to minimize the total electric power, drag force and the battery capacity for different UAV weights. Minimizing the battery capacity will reduce the take-off weight of the UAV and we can have more space for payload. Figure 65 indicates the pareto front plot for the three objectives. The arrows indicate the chosen points for the best optimal solutions since these points can give the best desired outputs.

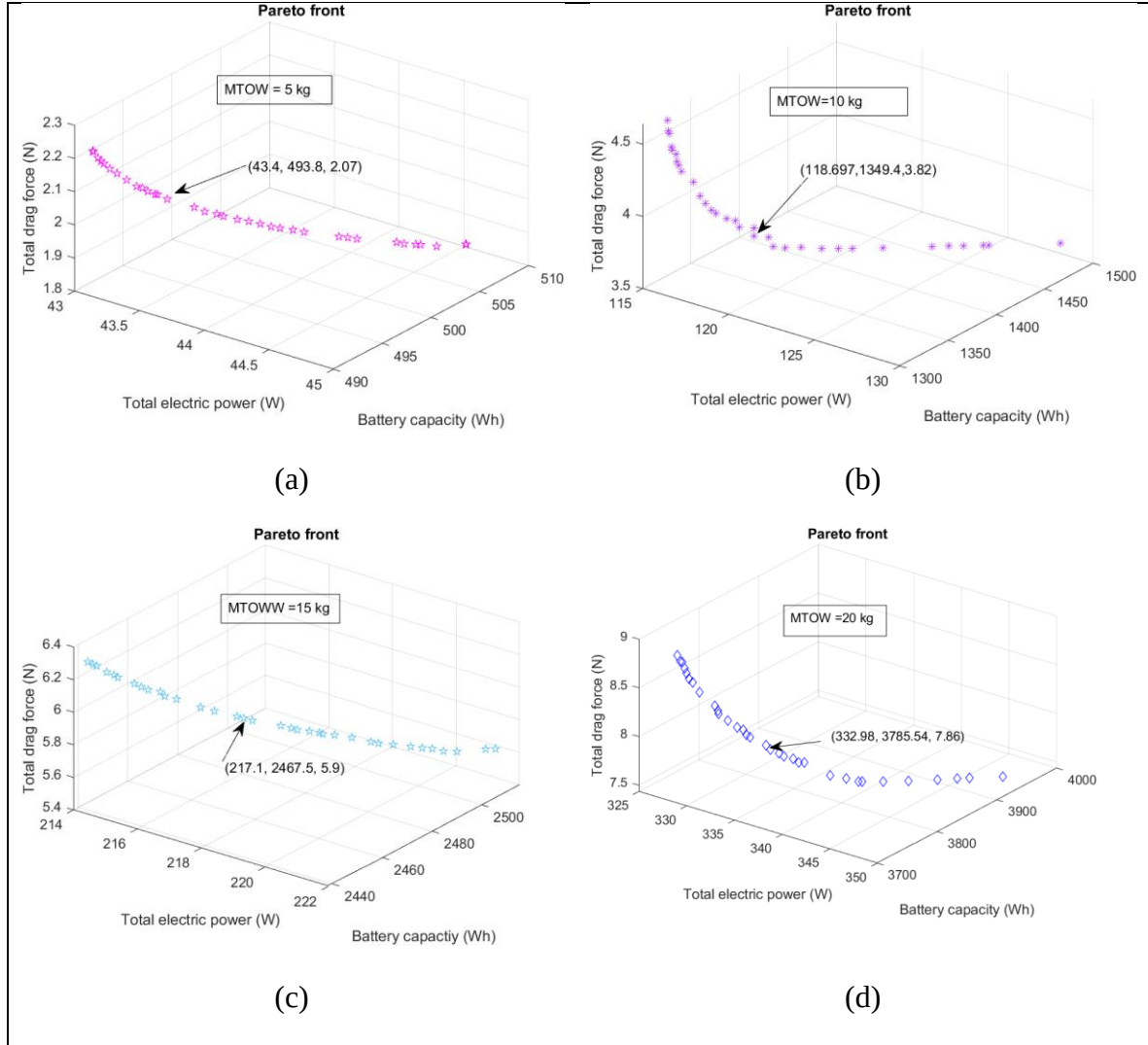


Figure 68. Pareto front for four MTOW UAVs in terms of total power, total drag force and battery capacity.

Table 9 shows the design variables' parameter values for four UAV takeoff weights. As indicated in Table 14, both high aspect ratio and wingspan achieve better performance; for all different UAV weights, the aspect ratio is between 15 and 18 which are close to the maximum AR limit used for the optimization. Similarly, high wingspan is favored. For the battery energy density, the optimum values range from 203 to 225 Wh/kg, and for the altitude, the optimal altitude for the smallest UAV weight (5kg) is 2297 m and for the other three weights, the optimal altitude is about 1300 m. It can be indicated that, for all four

weights, the battery endurance is almost the same, which is about 11.3 hours. This means that all UAVs can fly continuously for 24 hours assuming that the daytime is 13.2 hours.

Table 14. Chosen design variables and objective functions outputs.

UAV mass	Input variables				Optimum output solutions			
	Wing span b (m)	AR	Energy density of the battery (Wh/kg)	Altitude (m)	Total electric power (W)	Battery capacity (Wh)	Total drag force (N)	Battery Endurance (h)
5 kg	5.49	15.3	217.9	2297	43.43	493.77	2.06	11.39
10 kg	5.5	18.6	203.6	1310.1	118.697	1349.4	3.82	11.368
15 kg	5.5	17.3	223.6	1382.3	217.1	2467.5	5.9	11.365
20 kg	5.5	17.3	225.4	1386.3	332.98	3785.54	7.86	11.368

4.4.2 Hybrid solar/ battery UAV Energy Balance Analysis and Discussion

The proposed UAV design was supposed to operate at a constant speed and altitude throughout the day, which kept the required power constant. This was not a completely irrational assumption. There would be no need for an altitude change if the plane started the day flying and did not land. In excellent weather, a capable pilot or autopilot could maintain altitude and velocity quite effectively. The fundamental assumption was that steady wind, gusts, rising air, or sinking air would not vary the power necessary to maintain flying considerably. This assumption's correctness was determined by the actual weather conditions at the time of flight. It is simpler to neglect the weather conditions for the design analysis.

The energy balance assumed that the aircraft would fly above Dhahran, KSA, which is

located at a latitude of 26.23° . The geographic latitude has a great effect on the excess solar power and the length of sunlight hours. The analysis is done for two different periods of the year, 21st of June and the 21st of November. The specification and design variables of the proposed UAV used for this model analysis is mentioned in Table 15. The UAV is integrated with hybrid solar PV panels and a li-Po battery.

Table 15. UAV designed input parameters.

Aerodynamic	Aspect ratio	13.3
	Cruise speed (m/s)	8.5
	L/D	22
	CL	0.8
	Oswald constant e	0.9
	Wing area (m ²)	1.875
Payload	Mass (kg)	2
	Power (W)	0
Battery	Specific energy k_{batt} (Wh/kg)	240
	Efficiency	0.95

	Efficiency of charging η_{chrg}	0.95
	Efficiency of discharging η_{dchrg}	0.95
PV	Density (kg/m ³)	0.32
	Efficiency	0.21
	Encapsulation (kg/m ³)	0.26
	η_{MPPT} efficiency	0.95
Propeller	Propeller efficiency η_{prop}	0.8
	Gearbox efficiency $\eta_{gearbox}$	0.95
	Motor efficiency η_{motor}	0.85
	Controller efficiency η_{mctrl}	0.97

The output parameters for the proposed UAV are represented in Table 16.

Table 16. Preliminary output parameters.

Wing loading (N/m ²)	1.875
Take-off weight W_{to} (kg)	7

Wingspan (m)	5
Solar cell mass (kg)	1.688
Battery mass (kg)	3.5

Figure 69 represents the energy balance diagram for 48 hours cycle that can be repeated on the 21st of June. As the figure indicated, the solar consumed area will operate during sunlight hours. The excess energy of the solar cell will be used to charge the battery. After charging the battery, the remaining solar energy will be stored as potential energy, so the UAV will start gaining altitude (solar climb area). At the beginning of the night, the UAV will glide for about 1 hour. The battery will start operating until it is drained before the next day's sunset. The energy margins for the 21st of June are depicted in Table 17. There's been 3.7 % more solar energy (873 Wh) available to charge the battery than the battery capacity (840 Wh). This battery capacity was 21.4 % greater than the energy required to store solar energy if altitude was not utilized (660 Wh). Even though Figure 69 demonstrated how much energy might be saved by employing altitude energy storage, the battery capacity was conservatively chosen such that it did not rely on height to store energy. Storing surplus solar energy as altitude may not even be possible if the altitude required exceeds regulatory constraints [237]. If altitude storage is possible, the battery capacity margin rises to 25.4 %. This demonstrated how advantageous elevation power storage might be, and there was enough extra battery capacity if altitude energy storage was used.

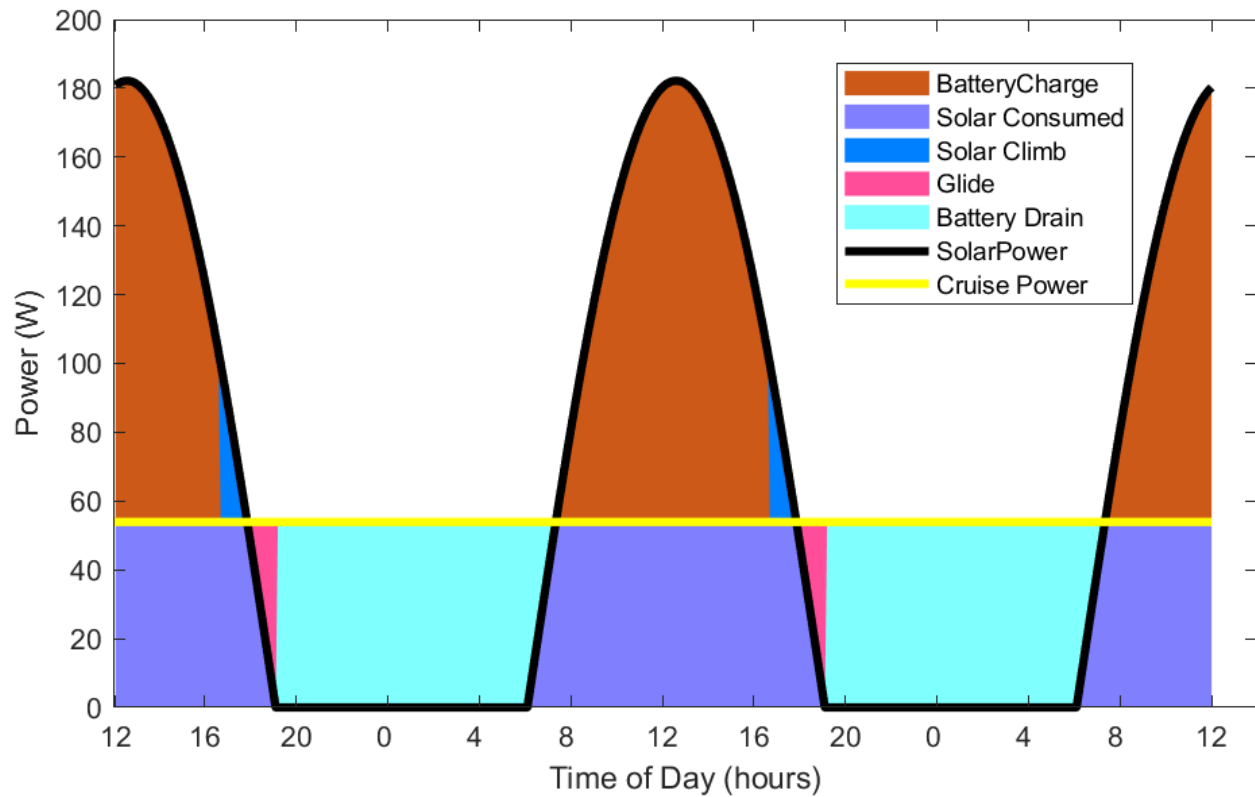


Figure 69. Energy balance over multiple days on 21 of June.

Table 17. Energy margins for 21st of June.

Available solar energy for charging	873 Wh
Battery capacity	840 Wh
Required battery energy without climbing	660 Wh
Required battery energy with climbing	627 Wh

Similarly, for the 21st of November, in which there are fewer sun hours and less solar irradiance, Figure 70 shows a continuous flight for more than 48 hours. The result indicated

that the solar energy was sufficient for charging the battery even if there was no excess solar energy that could be stored from gaining altitude.

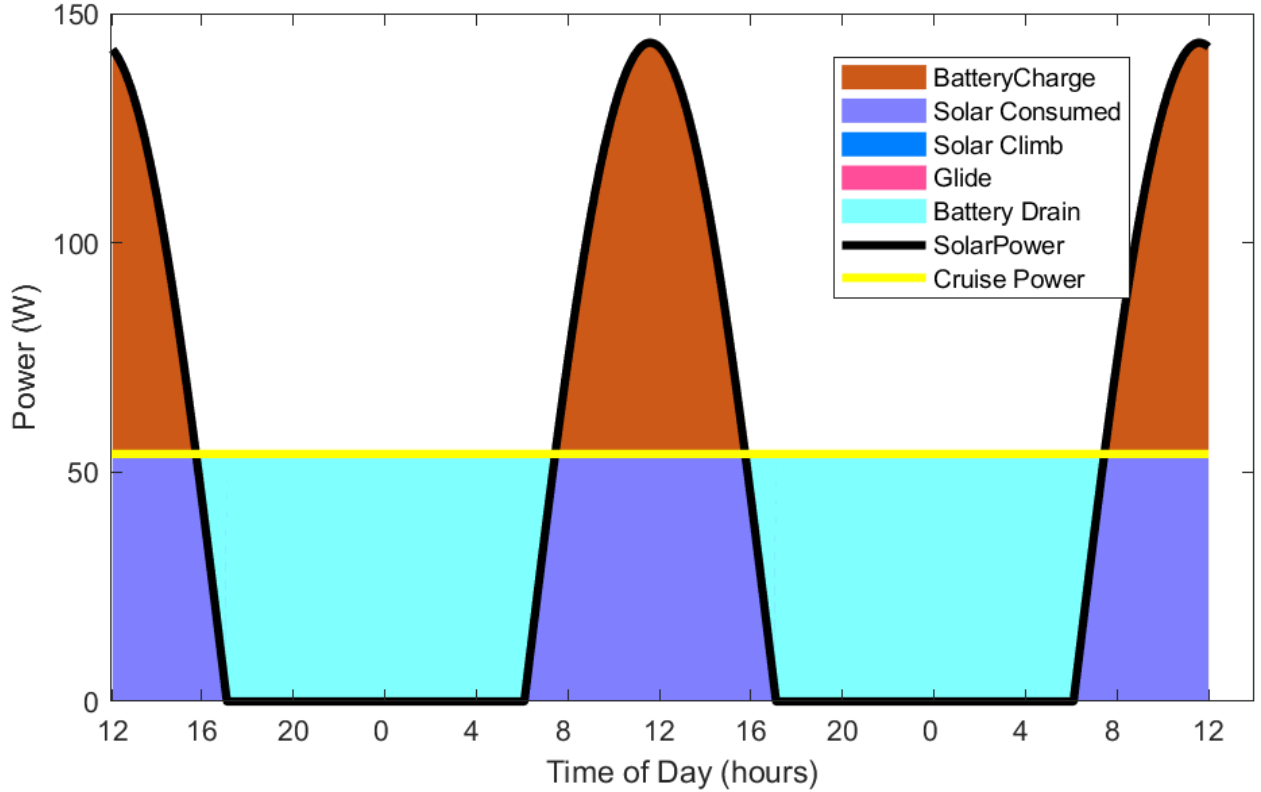


Figure 70. Energy balance over multiple days on 21 of November.

4.4.3 Hybrid SC + FC + battery Flying 24 Hours

Now integrating the fuel cell system with solar cell and battery into the UAV, the UAV still can fly continuously for 24 hours. This model is for low altitude 1000 m. The model parameter for Sky-Sailor model modification is mentioned in Table 18. The feasibility begins with a wingspan of around 25 m and ends at wingspan of 90 m. Figure 71 shows that the flying speed is rather slow and does not differ significantly from that of the Sky-Sailor airplane. This is the standard level flying speed, although during the day, an excess of energy from the fact that whether margin factor was incorporated in the design would allow the

aircraft to fly faster. The UAV integrated with fuel cell is favored for medium range missions, since the hydrogen storage needs to be refilled.

Table 18. Mission parameters of Sky-Sailor model UAV.

Parameter	Value
Payload mass m_{pld} (kg)	120
Avionic mass (kg)	20
Payload power consumption P_{pld}	0
Day length T_{day} (h)	13.2
Altitude (m)	1000
C_L	1

Figure 71a indicates a minimum wingspan of 25 m and maximum of 90 m. For low aspect ratio and larger wingspan, the total mass of UAV will be larger. Figure 71a shows a minimum UAV mass of 500 kg and maximum about 4000 kg, this is for low altitude long endurance UAV. The maximum level speed of the UAV can reach about 11 m/s which is quite low compared to conventional airplanes (see Figure 71b). The total electric power to drive the UAV increases with the increase of wingspan and low aspect ratio, if we have greater aspect ratio, the required power will be less as indicated in Figure 71c. The ratio of solar cell area to the wing area varies from 100 to 50 %, for instance, for the lowest aspect ratio ($AR=10$), the minimum solar area to wing area is 50 percent (see Figure 71d).

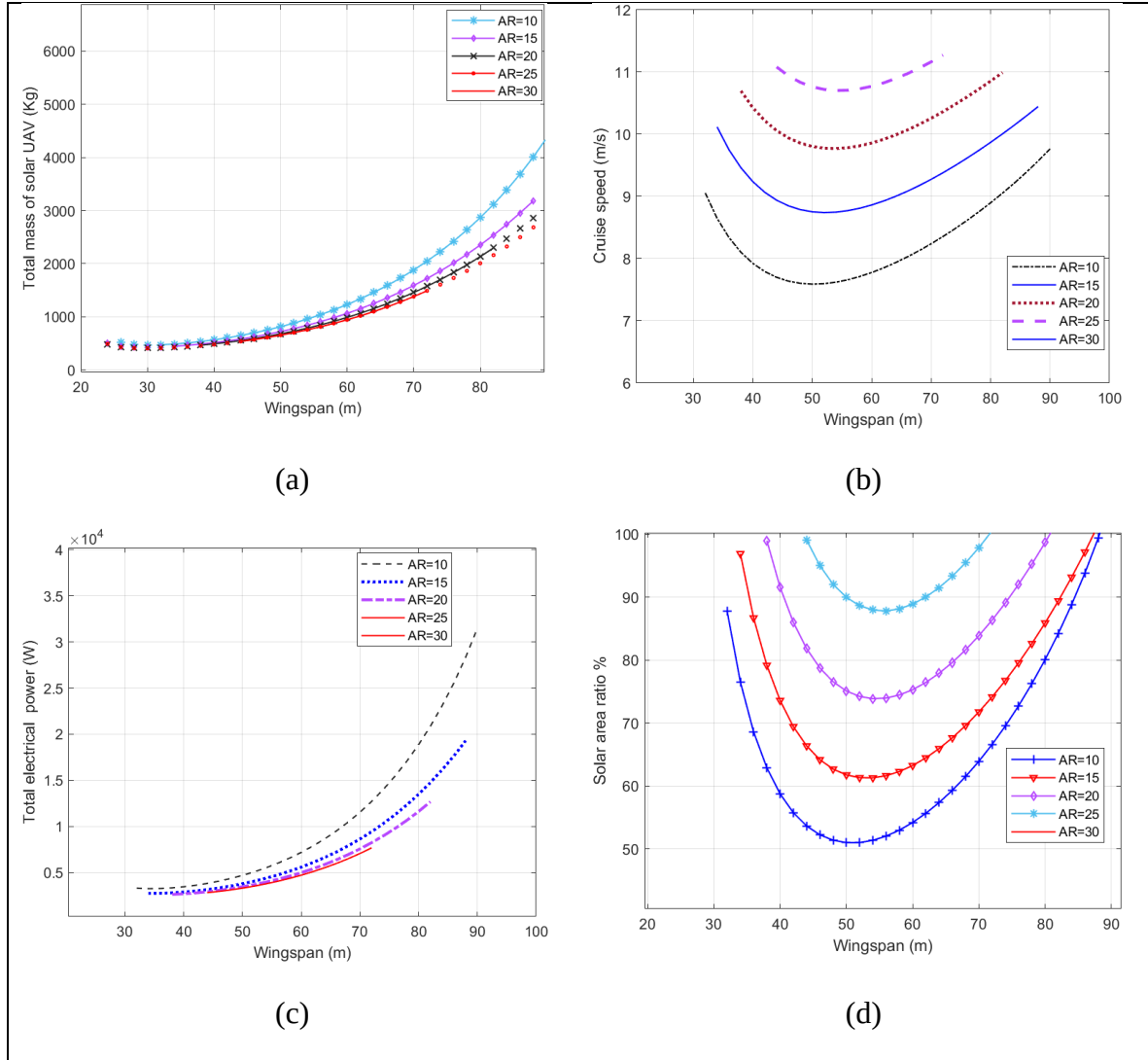


Figure 71. UAV flight characteristics in terms of wingspan and aspect ratio.

Table 19 indicates the output characteristics for UAV of 30 m wingspan and aspect ratio of 20. The mass distributed and different required powers are presented. The total UAV mass is 1477 kg. It can be noticed that the fuel cell stack is very small compared to the battery, because we need batteries for storing the power for flying during night. The fuel hydrogen needed for this mass is 70 kg. The fuel cell can supply continues power for 14.75 h until the fuel is drained, the battery will continue the flight next day and can be used as back up when fuel cell is working.

Table 19. UAV output characteristics for wingspan b of 30 m and AR 20.

Mass of battery (kg)	338
Payload mass (kg)	120
Airframe mass (kg)	741.71
Solar panels mass (kg)	112.39
MPPT mass (kg)	12.89
Fuel cell stack mass (kg)	6
Hydrogen fuel mass (kg)	70.21
Total mass (kg)	1477
Wing area (m ²)	245
Solar area (m ²)	193.78
Battery capacity (Wh)	81140
Maximum solar power (W)	30536
Total electric power (W)	7137
Level power (W)	5082
Fuel cell endurance (h)	14.75

For High altitude long endurance UAVs (MALE), the model is not feasible for high altitude such as 20000 m, due to the density reduction effect. The model can be feasible only if we have an energy density of 1000 Wh/kg of battery. Such a concept is not feasible today and needs future improvements in structure and energy storage methods, which could be batteries or regenerative fuel cells.

Applying the optimization technique for the UAV mentioned in Table 19, the upper and lower bound for the chosen design variables are mentioned in Table 20. The pareto front plot (Figure 72) indicates the objective function of minimizing the total electric power and maximizing the fuel cell endurance. Table 21 indicates the optimal input variable and the optimal solution. For the UAV of MTOW 1477 kg, the fuel cell endurance has increased by 1.11 hour, and the total electric power has decreased by 231.2 W.

Table 20. Preliminary upper and lower boundaries for input design parameters.

Design Variable	Upper bound	Lower bound
Wingspan b (m)	25	80
Aspect ratio AR	10	30
Energy density of fuel cell (Wh/kg)	550	1500
Altitude (m)	1000	30000

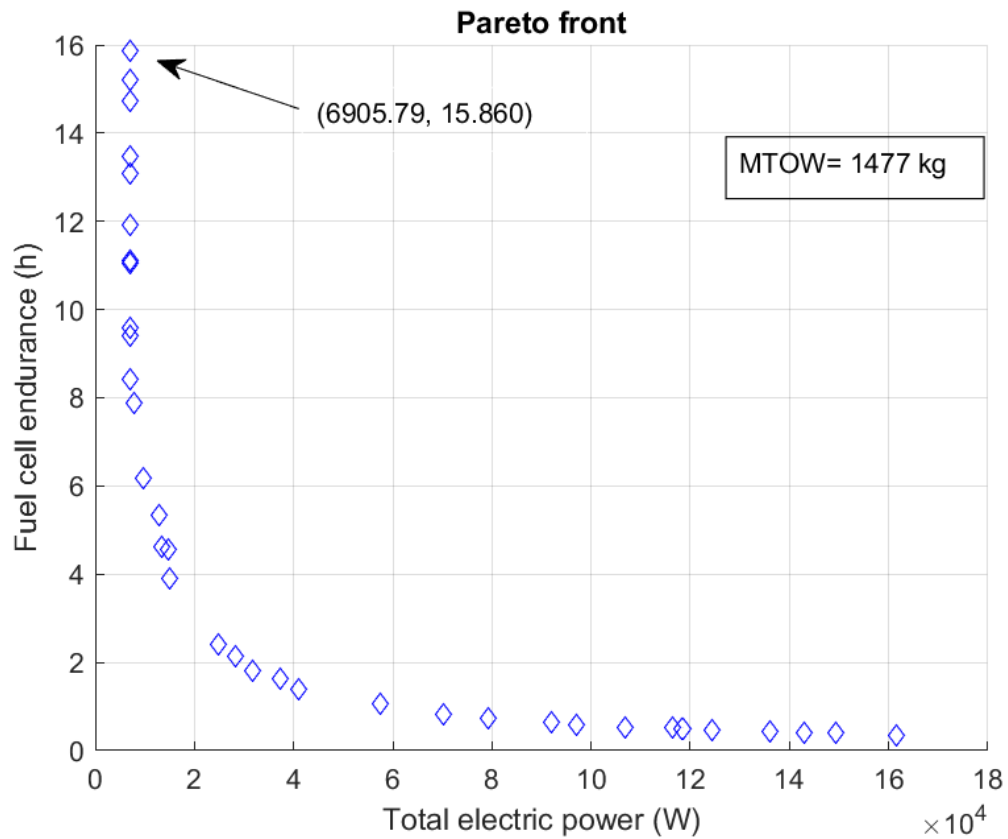


Figure 72. Pareto front for MTOW UAVs of 1477 kg in terms of total power, and fuel cell endurance.

Table 21. Chosen design variables and objective functions outputs.

Input variables				Optimal outputs	
Wingspan b (m)	AR	Energy density of the FC (Wh/kg)	Altitude (m)	Total electric power (W)	FC Endurance (h)
80	18.8	1131	1434	6905.79	15.86

Similarly, performing an optimization for small UAVs powered by full hybrid system (Solar + battery +Fuel cell) is analyzed for different four small UAVs weights. The preliminary upper and lower boundaries for input variables are shown in Table 22.

Table 22. Preliminary upper and lower boundaries for input design parameters.

Design Variable	Upper bound	Lower bound
Wingspan b (m)	3	10
Aspect ratio AR	8	25
Energy density of Fuel cell (Wh/kg)	550	1500
Weight of hydrogen fuel (kg)	1.2	3
Altitude (m)	500	30000

The pareto front plots illustrated in Figure 73 indicate the optimal objective outputs. The objectives here are to minimize the total electric power and maximize the fuel cell endurance.

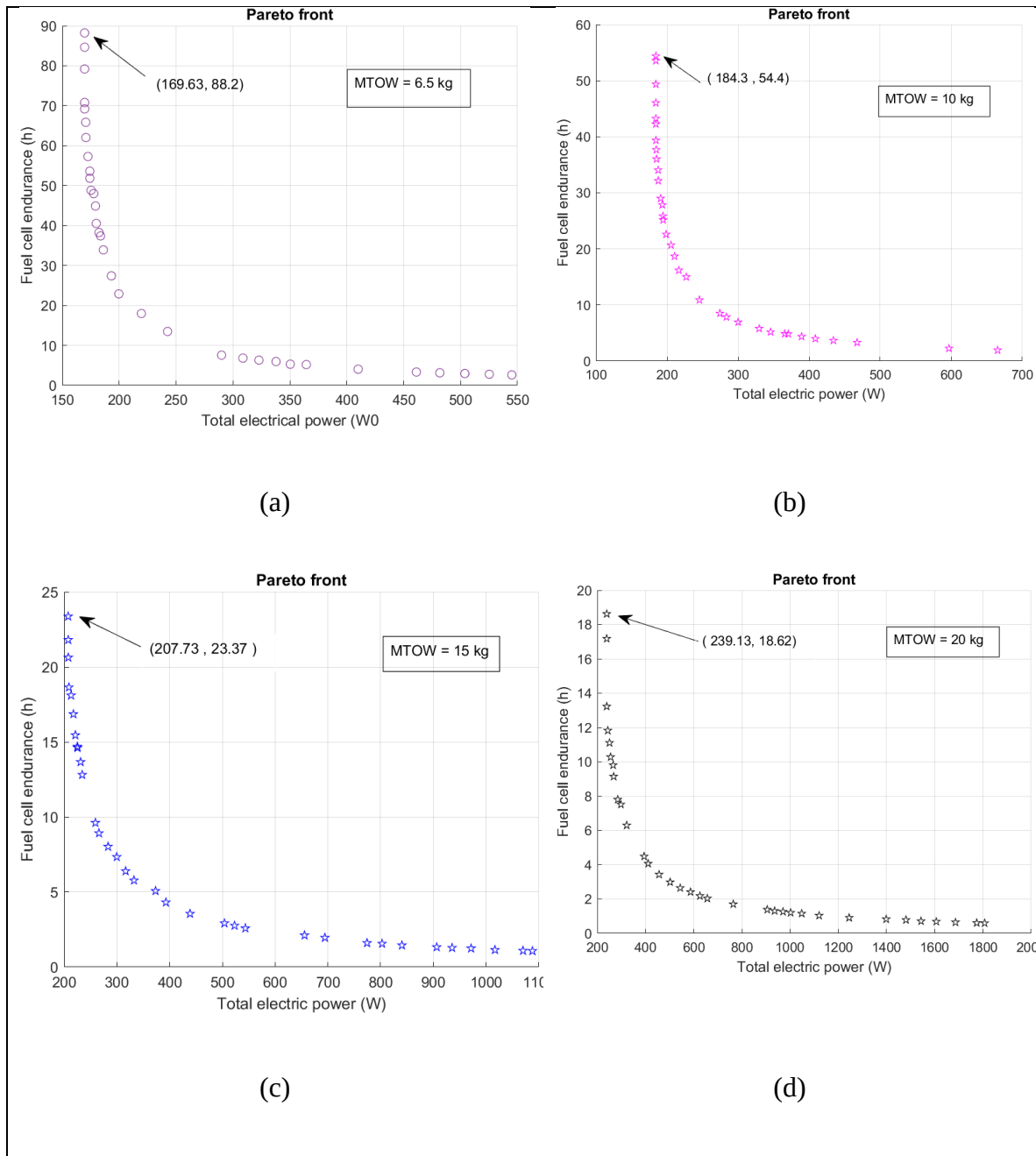


Figure 73. Pareto front for four MTOW UAVs in terms of total electric power, and fuel cell endurance.

Table 23 shows the chosen input variables for optimal output for different UAVs weights. The wingspan and aspect ratio optimal values are quite high and close to the maximum boundaries. The fuel cell energy density is above 600 Wh/kg, and the altitude is still low altitude. The weight of hydrogen does not exceed 2 kg. for the optimum output, we can see

that for the lightest UAV (6.5 kg), the total power is quite low (about 169.3 W), and the flight time will be 88.2 hours which means the UAV can fly during nights for multiple nights. For the largest UAV weight 20 kg, the time endurance is 18.62 hours which is enough for the UAV to fly for 24 hours continuously.

Table 23. Chosen design variables and objective functions outputs of full hybrid system.

UAV weight	Input variables					Optimal output	
	Wingspan b (m)	AR	Energy density of the FC (Wh/kg)	Hydrogen weight (kg)	Altitude (m)	Total electric power (W)	FC Endurance (h)
6.5 kg	10	18.5	684.88	1.28	1454.3	169.3	88.2
10 kg	9.99	18.1	698.48	1.73	1715	184.35	54.4
15 kg	10	17.2	648.05	1.41	898.75	207.73	23.37
20 kg	9.99	18.1	668.56	1.73	1472	239.13	18.62

CHAPTER 5 MAPPING AND COMPARING AMONG DIFFERENT POWER SOURCES

A summary of each of the sources of power is provided, along with some of its primary pros and limitations. The advantages and disadvantages of each power source are discussed in this chapter to show the potential opportunity for enhancement. This is illustrated in Table 24.

Table 24. Advantages vs. disadvantages of FC, batteries, and solar power sources.

	Advantages	Disadvantages
Fuel cells	No pollution, no noise, high energy density, and can recharge quickly.	Large size, the hydrogen tank size can limit the drone design and build. Low dynamic response
Batteries	Smaller, fast response, lightweight	Low energy density, limited capacity, lower endurance.
Solar	Unlimited power from the sun, quit, low operational time, friendly to the environment	Required large wing area for the PV panels, hence, more size, it can be affected by the weather conditions, much heavier than FC and battery.

		Limited to the fixed-wing UAVs
Hybrid	Longer endurance, high energy density	Bulk size, heavy, limited by recharge rate and cycles of batteries.

After analyzing the three power sources, the fuel cell power source has the highest energy density, and they are the best option for low-range fixed-wing UAVs; the fuel cells have a larger size and weight compared to the batteries, and the hydrogen tank can be bulky. The fuel cell propulsion system for fixed-wing UAVs will be placed inside the fuselage (depending on the power management system). For rotary UAVs, the fuel cells system and tank can negatively affect the weight and the maneuverability of the UAV. In the case of battery power sources, they are very suitable for mini and very small (2-4 kg) rotary drones. Rotary-wing UAVs require more powerful propulsion systems and a more dynamic power profile than fixed-wing UAVs. As a result, applicable fuel cell hybrid systems (FC + battery) need a greater nominal stack power and degree of hybridization than fixed wings. Because fuel cells have a limited dynamic response, batteries are critical for maneuverability. Inadequate hybrid management might result in fuel shortage and membrane degradation. There is a significant difference between the fixed-wing UAVs driven by fuel cells, and the rotary UAVs driven by batteries. This difference is due to the power contribution from the fuel cell and the battery. Generally, fixed-wing UAVs have a modest and consistent power requirement throughout cruising mode. The fuel cell may then be designed to meet that

power consumption, limiting the battery's responsibility to solely supply power for a sudden response, climbing mode and maneuvering. For solar power sources, solar and hybrid solar with battery is only limited to fixed-wing UAVs. This system can have double the flight time of the other sources, and it is favored for the MALE and HALE UAVs, also for large UAVs. This source has unlimited power from the sun. However, it can be affected by weather conditions, geographic locations, and sunlight hours. Furthermore, in terms of flying length and cost-effectiveness, battery-powered platforms may meet the needs of a wide range of hobbyist applications. However, typical tiny battery-powered UAVs have a limited endurance due to battery pack weight limits. They can fly for up to 90 minutes on LiPo batteries.

Table 25 illustrates the different characteristics of FC, battery, and solar cell power sources. These power sources are integrated into different UAVs, as mentioned in the above sections. The fuel cell and solar cell are integrated into fixed-wing UAVs, while the battery is integrated with multirotor drones. Comparing the three power sources, a reference point of payload capabilities of roughly 3 kg for each UAV was selected, allowing for a more realistic comparability of the sources (see Table 25). It should be mentioned that the flight endurance for fuel cell UAVs depends on the fuel tank size.

Table 25. Comparison between the different features of the three power sources.

Metrics	FC	Battery	Solar
Energy density (Wh/kg)	550	240	430
Endurance (hours)	7	1	≥ 48
Payload (kg)	3	3	3
Weight (kg)	6.5	25	7
Size category	Small	Small	Small
Total Power (W)	1195	2500	250

A point of reference will be necessary to compare the various UAVs. In this study, the ratios of endurance to weight, payload to endurance, and payload to weight will be the basis. Table 26 displays these values. For the first ratio, a number greater than one is desirable and the larger the better, as this suggests that the UAV's endurance is less impacted by its weight, resulting in lower losses. The second ratio favors values that are smaller but closer to one since they indicate a reasonable flight time while still incorporating payload capabilities, which is advantageous because it can have a broader area of use. In the case of the third ratio, values greater than 0 indicate that the UAV can carry a weight greater than its own,

expanding its area of applicability; the greater the value, the better. This is indicated that the fuel cell has the best endurance-to-weight and payload-to-endurance ratios; hence FCs have a long flight time, can carry a huge payload-to-weight ratio, and recharge rapidly, allowing them to have many more uses than most other choices. Batteries have the best ratio of payload to weight which make them be able to carry about 36 % of their weight.

Table 26. Comparison of power source ratios.

Power source	Endurance (hours)	Payload (kg)	Payload (kg)
	Weight (kg)	Endurance (hours)	Weight (kg)
FC	1.07	0.4286	0.06
Battery	0.04	3	0.36
Solar	0.145	0.0625	0.14

Figure 74 indicated different propulsion systems comparisons based on peak power, endurance, and size. The battery is the best option only when considering the size since it has the smallest size; however, the battery has the lowest flight time but the highest peak power. The fuel cell can be the best option since it has a good balance between endurance and size. For solar or hybrid solar systems, they have the longest endurance but bulk size. From this analysis, we can choose the proper power source for the most suitable UAV type based on the mission or applications.

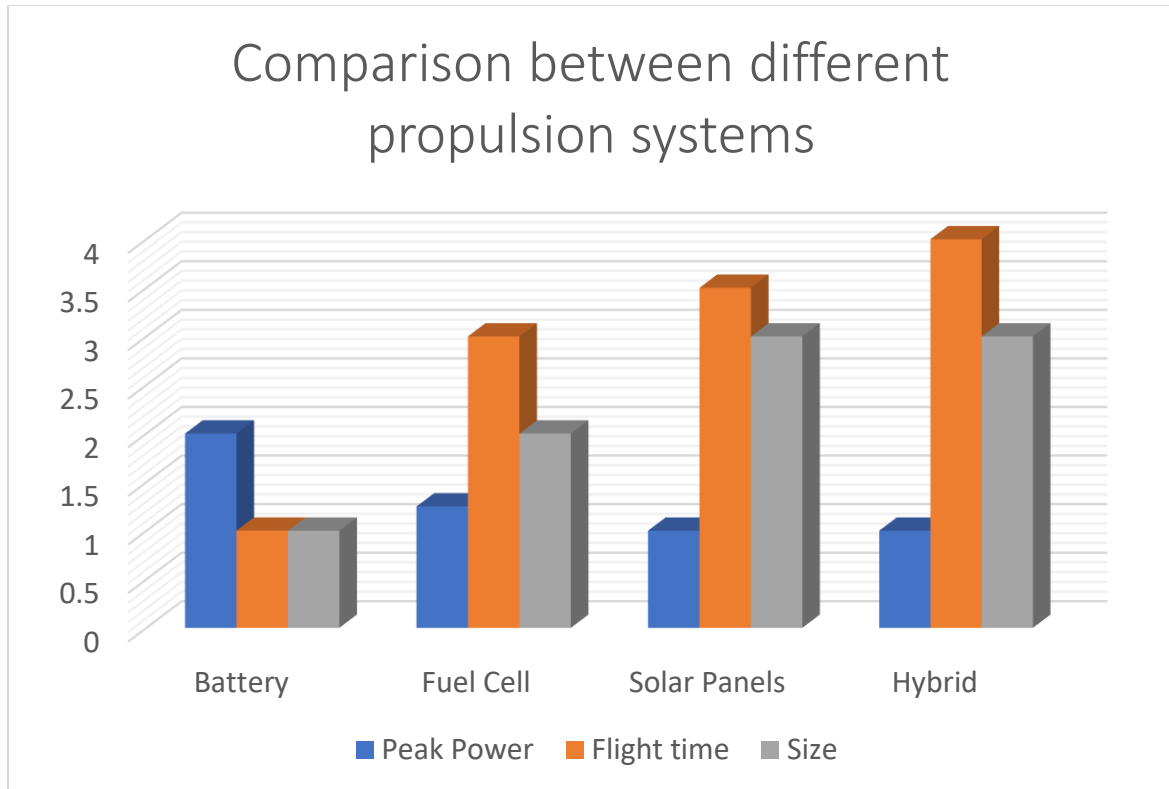


Figure 74. Comparison between different propulsion systems based on peak power, time flight, and size.

Table 27 shows a comparison between different propulsion systems integrated to different UAVs, the comparison is done based on the required power and endurance for different systems. The ratio of the power system to the maximum UAV takeoff weight is illustrated as well in Table 27. This ratio indicates how heavy the power system is compared to the total UAV weight. The solar and battery systems have the lowest power weight to UAV weight ratios which are 0.245 and 0.319 respectively. The fuel cell system has a ratio of 0.423 which makes it heavier than battery or solar. Finally, hybrid systems have the largest ratios which make them the heaviest systems and for the large UAV scale, the ratio is lower than the fuel cell because we do not need for very heavy fuel cell to produce large power, unlike the batteries which works as energy storages.

Table 27. General comparison among different power sources based on power, endurance, power system to MTOW ratio and suggested applications.

Power system	UAV weight (kg)	Cruise power (W)	Flight time (h)	Power system weight (kg)	Power sys. weight MTOW	Suitable application
FC	6.5	43.4	20	2.748	0.423	offshore inspection, search and rescue, aerial photography and mapping, precision agriculture
Battery	25	2500	0.4166	7.98	0.319	Aerial Photography, Videography, and entertainment
Solar	2.5	33.729	7.3	0.6115	0.245	Aerial Photography, Videography
Hybrid SC +batt	7	58	≥ 48	5.188	0.741	Mapping & Surveying

Full hybrid (6.5 kg)	6.5	169.3	≥ 88.2	3.89	0.598	Mapping & Surveying
Full hybrid (large UAV)	1477	5082	≥ 48	539.49	0.369	continuous surveillance and communication in places with inadequate or non-existent network infrastructure

After analyzing and comparing each power source, Table 28 illustrates a scaling technique to map each power system with the most proper UAV type. The scaling is from 1 star to 5 stars, the one stars represents the worst option, and the five stars represents the best option. The scaling technique is based on the optimal values of required power and flight endurance. If the UAV with a specific power system has the lowest power (compared to other power systems), then it has 5 points out of 5, similarly, if it has the highest endurance. After that, we will consider the total points out of 10. Furthermore, when the UAV with a specific power system has the highest power (compared to other power systems), then it has 1 point out of 5 and when it has the lowest flight endurance, it will have 1 point out of 5. The UAV with the highest total points has 5 stars and the UAV that has the lowest total points has 1 star and so on. The results indicated that the fuel cell source could be the best option for the generally

very small and small UAVs compared to other power system, however, the only fuel cell system is not applicable for mini and UAVs such as HALE. The batteries are most suitable for mini and very small UAVs. They perform poorly in long-range UAVs, and they are mostly used as a backup power source or as energy storage for other sources. This is because they have high power response, and they don't need time to start up like fuel cells. In the case of solar panels sources only, they have less performance for very small and small UAVs compared to fuel cells and batteries sources, and they are not applicable for mini or large UAVs. Hybrid systems such as solar/battery and solar /fuel cell/battery are most suitable for long-range, long endurance such as large UAVs such as HALE. The hybrid system, such as the solar cells and the battery, are not applicable for mini and very small UAVs because the hybrid systems are heavy and require more weight. For this reason, the best option is applying this hybrid system to small UAVs, additionally, this type of hybridization is not working for HALE UAVs because batteries cannot operate in high altitude unless their energy density is more than 1000 Wh/kg, which is not available. For the full hybrid system, with solar, battery and fuel cell, this system is the best choice for HALE and is very good in small UAVs as well.

Table 28. Mapping each power source to a suitable UAV type.

Power source	Mini UAVs (≤ 100 g)	Very small UAV (0.1-3 kg)	Small UAV (4-25 kg)	HALE
FC	NA	★★★★★	★★★★★	NA
Batteries	★★★★★	★★★★★	★★	NA
Solar	NA	★★★	★★★	NA
SC/Batt	NA	NA	★★★★★	NA
SC+FC+Batt	NA	NA	★★★★★	★★★★★

CHAPTER 6 CONCLUSION AND FUTURE WORK

This thesis study evaluated different renewable and clean power sources, including fuel cells, batteries, and solar panels. The study introduced a mathematical model for each power source. Each model is then integrated into a UAV propulsion system. The performance of each power source, such as required power and flight endurance, has been investigated. Additionally, the study presented an optimization technique to obtain the best design variable to power different UAVs sizes. Hybrid power sources of solar cells / batteries and solar cell / fuel cell/ battery are investigated. A comparison and mapping technique was proposed to evaluate and determine the best power source for suitable UAV types. The results indicated that the fuel cell power source could achieve higher endurance time than the batteries. Fuel cells can be the best option for small fixed-wing UAVs, and they have better performance than batteries. The battery power source has the lowest endurance time, and they are more suitable for mini and very small drones. For the solar cell power cell, it is only suitable for fixed-wing UAVs, and it can have double flight endurance than batteries. Hybrid solar systems can last more than 48 hours, and they receive unlimited energy from the sun. However, they can be affected by weather conditions. Additionally, the hybrid system is heavy and bulky. Moreover, the high-altitude long endurance UAVs cannot operate under hybrid solar + battery unless we have a battery with an energy density of 1000 Wh/kg, so, regenerative fuel cells can be used to solve this issue.

For successful development of UAVs powered by fuel cells or hybrid systems, the following suggestions should be considered.

- Fuel cell aircraft performance evaluation and optimization in severe operating circumstances such as summertime, midwinter, rainy days, or high altitude.
- Improvement the fuel cell durability and reactor design to optimize hydrogen generation rate and to prevent borate clogging.
- Integrating UAVs with a hybrid conventional combustion engine and fuel cell.
- Studying the hybrid system of fuel solar cells with supercapacitors.
- Studying regenerative fuel cells with solar systems for high altitude long endurance UAVs.

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