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Review of Power Device for Solar-Powered Aircraft Applications

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ABSTRACT: This paper reviews various power device components of solar-powered aircraft such as photovoltaic (PV) cells, maximum power point tracker (MPPT) and rechargeable batteries. The various power device components were highlighted, and the ones applicable to aircraft were analyzed, based on criteria as efficiency for photovoltaic cells; energy densities about rechargeable batteries; and maximum power point tracker on quick response to achieve maximum power point on I-V curve. Emerging technologies like photovoltaic cells, thin film cell, organic photovoltaic cell, multi-junction cell and silicon quantum dot cell, with the future potential of high efficiencies that can be used in solar-powered aircraft, were all examined. Regarding battery technology, Lithium-air battery (Li-air) was reported as having great opportunities for high energy densities capable of improving the efficiency of the solar-powered aircraft, for the greater prospect of the aviation industry. The design of efficient power device for solar-powered aircraft application is proposed. Gallium Arsenide (GaAs) solar cells were used because of its high energy conversion efficiency of 30 to 40%. A smart and intelligent MPPT Artificial Neural Network (ANN) is chosen because of its efficiency in partial shading and fast response and speed. The Li-air rechargeable battery is proposed because of its theoretical energy density of 11680 Wh/Kg.

KEYWORDS: Solar powered aircraft, Rechargeable battery, Photovoltaic cell, Maximum power point tracker.

INTRODUCTION

Solar-powered aircraft is a remarkable concept, cutting-edge technology, and the aircraft for the future (Cleave 2008). The unlimited availability of solar radiation makes this masterpiece green technology look very promising regarding affordability, safety, sustainability and clean means of transportation (Bicer and Dincer 2017). To build the aircraft that can demonstrate enormous capability for continuous flight (Colozza 2004; Zhang *et al.* 2017), the idea of solar-powered aircraft design equipped with power device that includes photovoltaic (PV) cells, rechargeable batteries and maximum power point tracker (MPPT) (Reddy and Aneesh 2017; Frulla and Cestino 2008) was conceived. The PV cells are installed on the wing – the solar energy converts into electrical energy that is used to power the propulsion system and the avionics. The rechargeable battery is situated on the fuselage or any other appropriate part of the aircraft. It is used to store energy at day-time and supply power to the systems at night-time (Gao *et al.* 2015).

The changeable phenomena of solar energy and mode of application of solar-powered aircraft makes it imperative to analyze the power components and to come out with robust energy management and operation to accomplish a nonstop flight of 48 h (Ramírez-Díaz *et al.* 2015; Klöckner *et al.* 2012). For aircraft powered by solar to attain a continuous flight, Energy Management

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System (EMS) is required (Shiau *et al.* 2009). For a photovoltaic cell to produce optimal energy, MPPT device is essential. The MPPT tracks and monitors the current and voltage of the photovoltaic cells and rechargeable batteries (Noth *et al.* 2004). By varying the gain, it allows for the optimal energy to be extracted from the photovoltaic cells (Tsang and Chan 2013). In the Aircraft powered by solar, the MPPT is integrated into the EMS.

This paper aims to analyze the power devices of solar-powered aircraft, with the goal of discussing the advances in technologies and the developmental trend of power devices in recent years, and designing more efficient solar-powered aircraft for the growth of the aviation industry. In this paper, the different types of photovoltaic cells, rechargeable batteries, and maximum power point tracker (MPPT) technologies related to solar-powered aircraft, and its advantages compared to conventional aircraft and its future applications are discussed.

NOTABLE AIRCRAFT POWERED BY SOLAR ENERGY

The first ever aircraft powered by solar energy was sunrise I, built in 1974. It was solar powered by monocrystalline and installed with 4096PV cells that produced 450 W of power and 11% efficiency (Boucher 1985). In 1980 the first ever human-crewed aircraft powered by monocrystalline was built by Dr. Paul MacCready, named as a Gossamer penguin. He also created Solar Challenger installed with 16,000 solar cells mounted on its wings, that generated 2500 W, without energy storage devices (MacCready *et al.* 1983). In 2005 Alan Cocconi produced SoLong with SunPower A300 monocrystalline solar cell, which provided a power of 225 W and storage device of Lithium-ion battery of 1200 Wh (Ross 2008). Zephyr 7, in 2010, had installed with amorphous silicon with 19% efficiency and a lithium Sulphur battery of 500-600 Wh/kg energy density (Mecrow *et al.* 2010). The Solar Impulse I, in 2009, is installed with monocrystalline solar cells of 11,628 with 18% efficiency and 84 W. Lithium polymer battery with an energy density of 240 Wh/kg was used (Leutenegger *et al.* 2011). And recently the Solar Impulse II flew around the world from 2014 to 2016. The aircraft was installed with 17,248 monocrystalline solar cells and produced a power of 66 KW and battery made of Lithium-ion (Hutchinson 2016).

SOLAR-POWERED AIRCRAFT POWER DEVICE COMPONENTS

The design of an solar-powered aircraft comprises of power components which include the photovoltaic cells, maximum power point tracker (MPPT) and rechargeable battery (Cleave 2008). Usually, the photovoltaic cells are installed in the wings and tail of the aircraft to convert solar energy into electrical energy to power the propulsion system and avionics. The battery is fitted in the fuselage and inside the wing or any other part of the aircraft. It charges during the day, when the solar energy is abundant, and discharges to power the aircraft and avionics at night. The nature of the solar radiation inclination, climatic condition, time of the day and year and cell orientation, make it impossible for solar energy to be available at optimum level at all time (Rajendran and Smith 2015; Pande and Verstraete 2018). MPPT is used to get maximum solar energy from the photovoltaic cells. The MPPT track and ensure current and voltage works for a maximum power irrespective of changes in atmospheric conditions or load and optimizes the working of PV cells (Fazelpour *et al.* 2013). Figure 1 shows the power device of solar-powered aircraft.

PHOTOVOLTAIC CELL

PV cell translates solar energy into electrical energy. A P-N junction displays a voltage and current intricate link in the solar cell (Arjyadhara *et al.* 2013). When the solar light falls on the cell, voltage and current are the products which show the intricate connection between insolation and output power (Dimova-Malinovska 2010). Under a bright light condition, the solar cells capture slows moving low energy electrons. Energy is lost due to saturation of the solar cell (Bialasiewicz 2008). When the insolation is low, the power generated will be high, while higher insolation will reduce generated power due to the saturation of cells, and the number of free electrons or their mobility decreases significantly (Esram and Chapman 2007).

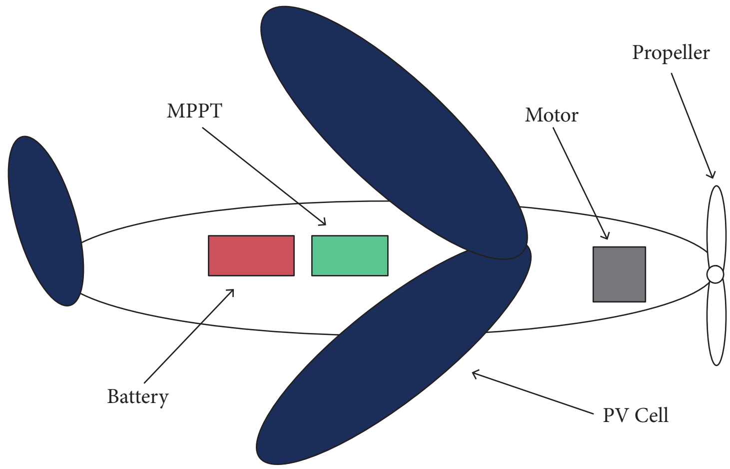

Figure 1. The power device of solar-powered aircraft (Gao *et al.* 2015).

Figure 2 shows the I-V characteristic of the intricate link between voltage and current relationship. The open voltage is the voltage across the terminal in an open circuit and the short circuit current is the current passing through the wire is short-circuited while the voltage is zero.

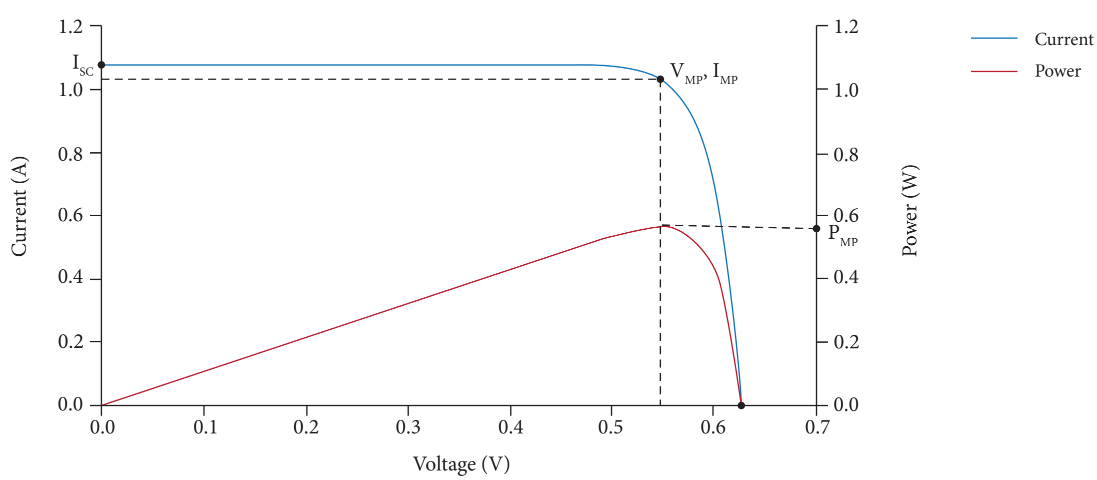

Figure 2. I-V Curve of a typical solar cell (Khurana *et al.* 2014).

CLASSIFICATION OF PHOTOVOLTAIC CELLS

Photovoltaic cells are classified based on the materials used for the solar cell production and groups as follows: crystalline silicon, thin film, organic/polymer, hybrid PV and dye-sensitized photovoltaic cell (Tyagi *et al.* 2013). Figure 3 shows the classification of PV cell based on PV material. The mode of PV cell energy operation is hypothetically similar, but varies in material and manufacture (Emery 2004).

The complementary effort of both researchers and manufacturers to reducing the production cost and improving the energy conversion efficiency of solar cells have greatly contributed to the affordability of solar energy (Abbe and Smith 2016). Although different solar cells types exist in the market, very few are applied to aircraft powered by solar energy due to the following reasons: capability of energy transformation efficiency, cost-consideration, environmental compliance, weight of the substrate, flexibility and consistency (Fazelpour *et al.* 2013). Silicon cell is the predominant photovoltaic cell used in solar-powered aircraft (Ghosh *et al.* 2017).

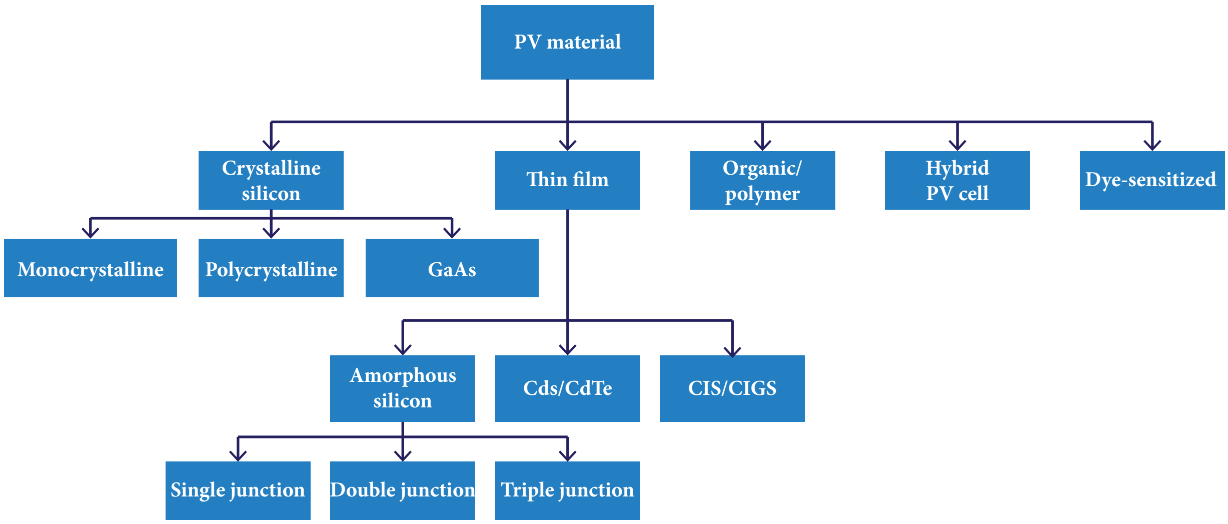

Figure 3. Classification of photovoltaic cell based on PV material (Tyagi *et al.* 2013).

Crystalline Material

Crystalline material PV cell comprises mono-crystalline, poly-crystalline and gallium arsenide (GaAs) cells. They are described as follows:

- **Mono-crystalline silicon** cell is a type of cell with a unique structure and uniform shape from a single-crystal (Arjyadhara *et al.* 2013). A pure silicon ingot produced from molted raw silicon. The silicon ingot is cut into thin wafers, polished, doped, coated, interconnected and assembled into modules and arrays. Monocrystalline silicon cells are mostly applicable to photovoltaic panel construction. The unique structure of the silicon wafer allows mobility of electrons from the material, which results in high energy conversion efficiency (Latukhina *et al.* 2015). Mono-crystalline cell has conversion efficiency between 15% and 20%. For PV cell to be applicable, the silicon has to be "doped" with other elements to make the required N-type and P-type conductive layer (Femia *et al.* 2006). Mono-crystalline cells are used for outdoor and solar-powered aircraft applications mainly due to their wafer thickness and conversion efficiency. However, monocrystalline cell application in solar-powered aircraft is faced with the problem of encapsulation of the solar cell on the cambered wing of the aircraft. Two methods are adapted to expertly bend the solar cell to follow the shape of the airfoil. In the first method, adhesive coating is used to lay the solar cell on the airfoil (Gao *et al.* 2015; Danjuma *et al.* 2018). The second method makes use of the flat-paneled airfoil specially intended for aircraft powered by solar energy (Chen and Bernal 2008).
- **Polycrystalline silicon** consists of different smaller grains of crystals which form the molecular structure, also creating boundaries between them (Becker *et al.* 2011). The energy conversion efficiency of polycrystalline cells is less compared to monocrystalline silicon cells due to limitations of electrons flow because the negative electrons are charged to form a union with the positive holes, resulting in reduced power output of the cell (Fraas 2014). The polycrystalline energy conversion efficiency is between 10 and 14%. These types of photovoltaic cells are cheaper to manufacture compared to monocrystalline silicon because of the reduced production cost (Khan and Arsalan 2016).
- **Gallium Arsenide** (GaAs) is a semiconductor material formed as a result of a combination of Gallium (Ga) and Arsenic (As), generating related or silicon-like structure (Becker *et al.* 2011). GaAs with a band gap of 1.43 eV has high efficiency and less thickness, when compares to the silicon-based solar cell (Kazmerski 2006; Iles 2001). Alloying with Aluminium, Indium, Phosphorus, and Antimony can increase the efficiency of GaAs. When GaAs is alloyed, a multi-junction device is formed, leading to an increase in the band gap value (Satyen 1998). Due to the high resistance of GaAs, it is applied in a concentrator PV module and space mission (Hillhouse and Beard 2009). The high energy conversion efficiency of 30% to 40% and the flexibility of the solar cell make it the best solar cell for solar-powered aircraft application. The solar cell

is flexible, so it can easily bend to the airfoil shape of the aircraft. The solar cell is more expensive than a monocrystalline solar cell, reason why it is not widely used.

The Thin Film PV Cell

This type of PV cell is manufactured directly by using a thin film semiconductor layer of PV material printed or sprayed on a glass, metal or plastic foil substrate (Aberle 2009). The PV cell thickness is smaller when compared to cut crystalline cell. The manufacturing process of this PV cell is faster and affordable because the PV is sprayed or printed on a glass and metal substrate. Thin film cells have higher light absorption capability compared to crystalline cells (Bossert *et al.* 2000), and they have low cell conversion efficiency due to the absence of crystalline structure, requiring more substantial sized cells. Cadmium Telluride, Amorphous Silicon, and Copper Indium di-Selenide or CIS are all types of thin PV cells.

- **Amorphous Silicon** (a-Si) cell is of a thin film structure with silicon extract but non-crystalline. This type of cell applies to small electronics products with low voltage rating. Amorphous silicon light absorption is 40 times higher than crystalline silicon (Meier *et al.* 2004). It gives amorphous silicon materials benefit because of the much thinner layer that is essential to produce a thin film PV cell, thereby making it very cheap in production and affordable. The advantage of amorphous silicon cells is that it can be stamped on various types of cheap materials, both flexible and rigid substrates, from polymers, thin metals, plastics, to tinted glass. The PV cell efficiency is 7% to 9%, and 5% when exposed to sunlight for a few months after installation (Meier *et al.* 1994). The low energy conversion efficiency affects its application in solar-powered aircraft.
- **Cadmium Telluride (CdTe) and Cadmium Sulphide (CdS)** is manufactured through thin CdS layer which evaporates on a conductive glass substrate, then a thick CdTe layer is evaporated, and a metal contact layer is deposited to complete the process (Hegedus *et al.* 2007). The cell is heated with $CdCl_2$ flux that initiates crystallization of the semiconductor at a temperature of around 450 °C, and this permits copper CdS to be doped in a similar process (Hegedus and McCandless 2005). CdS/CdTe has been established to be stable for a very long time (Böer 2011). It can also produce an efficiency of 15% and 1.45 eV of band-gap due to high direct absorption coefficient (Britt and Ferekides 1993).
- **Copper Indium Gallium Selenide/Copper Indium Selenide** is the latest innovation that has a potential to contend with silicon solar cell. CIGS/CIS efficiency can reach up to 13% for a module and 20% for the cell (Repins *et al.* 2008). It can attain a high value of 1.68 Ev of bandgap with a small amount of change with Sulphur (S). The progress of CIGS solar cell was monitored under lifetime indoor (under STC) and outdoor for four months through an experiment carried out by Radue *et al.* (2009). Any trace of defects found in the module can cause a low current in the cell. An investigation of the progress of CIS and the similar thin-film cell was conducted by (Meyer and Dyk 2003). After the study, the results, when compared to another thin-film cell CIS, only reduced by 10% when exposed to 130 kWh/m^2 outdoor. The absorption coefficient of $CuInSe_2$ is above 105 cm^{-1}.

Organic and Polymer Cells

It is a relatively a new technology that looks promising and attracted the interest of researchers working on it because of the following reasons: physical flexibility, disposable, and cost-efficient material (Goetzberger *et al.* 2003). An investigation into the efficiency of the polymer cell used in PV-powered boats was carried out by McCann *et al.* (2001). The study was also carried out on properties of materials on the polymers, which include thickness, strength, density, UV stability, and temperature, among others. The results show that polymers have properties to replace silicon PV modules due to cost and weight factors in the nearest future. Organic materials have a significant disadvantage as PV cell because the highest open circuit voltage ever recorded was 4 V, which is very insignificant. However, the output voltage of organic materials increased due to use of broad absorption band material (Peumans *et al.* 2003).

Hybrid Solar Cell

A hybrid solar cell is formed by the fusion of crystalline silicon with non-crystalline silicon (Itoh *et al.* 2001). The integration of amorphous silicon with crystalline silicon produces a high-performance ratio of the solar cell (Itoh *et al.* 2001). The highest efficiency generated by hybrid solar cell was 21% by Sanyo solar cell (Tanaka *et al.* 1992). It is a combination of Heterojunction and Intrinsic thin film layers' solar cell (HIT). The base of this solar cell is an n-type CZ silicon wafer that functions as a light absorber. This type of solar cell can be used for solar-powered aircraft because of its energy conversion efficiency.

Dye-Sensitized Solar Cell

A type of solar cell that a semiconductor film produces by the photo-sensitized anode and an electrolyte. The surface of the semiconductor is absorbed with a sensitizer that contains an electrolyte with a redox mediator and counter electrode capable of regenerating the redox mediator like platine (Nazeeruddin *et al.* 2011). The dye-sensitized solar cell is a useful technology compared to the existing ones (Michael 2003).

THE EMERGING TECHNOLOGY TRENDS

In the area of solar-powered aircraft, several technologies are emerging, most of which are under research, while others are in the prototype stage. These technologies can improve the efficiency of the solar-powered aircraft.

PHOTOVOLTAIC

Thin-film technologies of solar cells have improved with time. Amorphous silicon cells are mostly produced from waste recycled computer chips. Various methods for manufacturing of thin-film cells include the followings: physical vapor deposition, plasma-enhanced chemical vapor deposition, and sputtering. As a result of improved performance when the temperature is high as opposed to crystalline silicon cells, thin-film cells application has dramatically increased (Han *et al.* 2017).

Multi-junction cells are mostly produced from Gallium Indium Phosphide (GaInP), Gallium Arsenide (GaAs), and Germanium (Ge) p–n junctions. They have the potential to convert much broader light frequencies. When compared to another solar cell, it hardly loses efficiency at high temperature and its efficiency can be greater than 40%. The recent technology can make it possible to get efficiency as high as 50% in the next ten years (Essig *et al.* 2015; (Danjuma *et al.* 2018). The multi-junction solar cell, due to its optimal conversion efficiency and flexibility, has an advantage in a future application in solar-powered aircraft (Pande and Verstraete 2018).

Quantum dots are innovations capable of boosting the efficiency of solar cells by increasing the value of the bandgap of solar cells to absorb more light in the solar spectrum so that it can produce charges efficiently from a single photon (Nozik 2002). Quantum dots solar cell have the capacity, theoretically, to translate 66% and above of the solar energy into electrical energy, almost expanding the efficiency of solar cells (Nozik 2002). Silicon quantum dot (SiQD) in dielectrics is the suitable material used for manufacturing of solar cell. The limitation of the decrease in the dimensions of the Silicon to less than 5 μm efficiently increase the bandgap, thereby increasing the cell efficiency (Nozik 2002).

Nanomaterials such as nano-wires and nano-particles have an advantage in applications compared to photovoltaic materials. The nanometer-size objects have a substantial interfacial area because of the significant surface area per unit volume. The nano size creates a quantum confinement effect, which provides an opportunity to design nano-materials with various bandgaps. The polychoral carbon nanotubes is a solar cell just like quantum dots; this can improve the bandgap and subsequently increase the efficiency to meet optimal requirements.

The technology can also be used to create an airframe of the aircraft. The thin film carbon nano-tubes and nano-fibers are typical examples of solar cell technologies. These have been indiscriminately adapted to and magnetically united, to be tenfold lighter and 500 fold stronger than steel (Gong *et al.* 2014). They exhibit electrical conductivity similar to copper or silicon and disperse heat identical to brass and steel. This characteristic adequately improved the performance of the solar cell and made it affordable (Dimova-Malinovska 2010).

In the nearest future, the aviation industry looks very promising with technological advancement and break-through research findings in aircraft powered by solar energy.

RECHARGEABLE BATTERIES

The rechargeable battery in aircraft powered by solar energy is vital to sustain continuous flight and high altitude and long endurance (HALE) (Barbosa *et al.* 2014). The rechargeable battery stores extra power during daytime and uses the power in the night.

Energy density is used to determine the efficiency of a rechargeable battery. The energy density is defined as the quantity of energy stored in a given system per unit mass. The energy density is given as (Eq. 1)

$$\bar{m}_b = \frac{E}{m_b} \tag{1}$$

where E is stored energy and m_b is the mass of the rechargeable battery (Gao *et al.* 2015).

Due to the significance of the energy density to the solar-powered aircraft, a consistent effort is being put up to improve the energy density (Braun *et al.* 2012). Figure 4 shows the power and energy density of various rechargeable batteries.

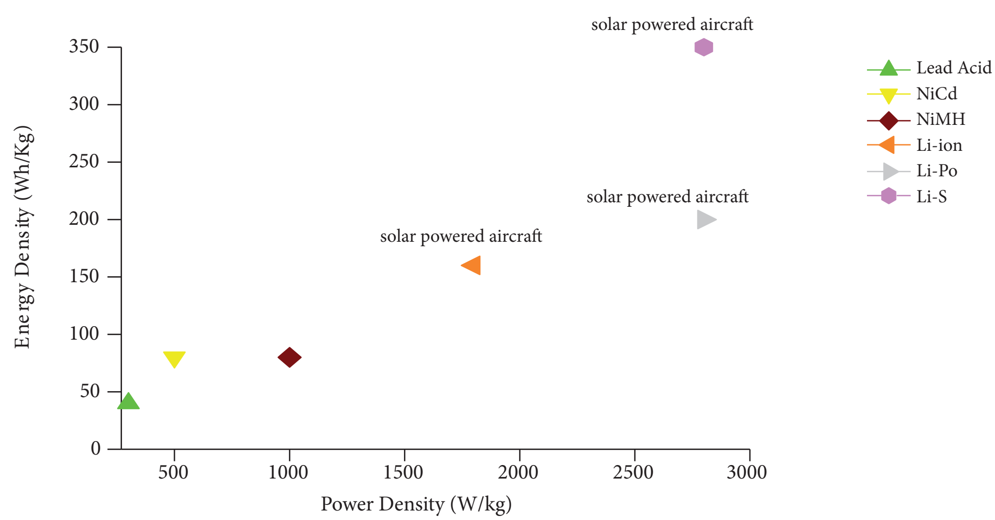

Figure 4. The power and energy density of various rechargeable batteries (Padbury and Zhang 2011; Braun *et al.* 2012).

A limitation of aircraft powered by solar energy is the low energy densities of the power propulsion. For this reason, high-energy density storage device is inevitable (Sliwinski *et al.* 2017). There are different energy storage devices, but their choice is determined by their area of application (Wagner 2007).

Classification of the Rechargeable Battery

Rechargeable batteries are classified from the early invention of Nickel-Cadmium, Nickel-Metal-Hydride to up to date invention of Lithium-ion, Lithium Polymer, and Lithium Sulfur, based on their energy densities.

- **Nickel-Cadmium Battery** has both Nickel and Cadmium electrodes in a Potassium Hydroxide solution. Early type battery uses an alkaline electrolyte (Rydh and Karlström 2002). The batteries are powerful and had a better energy density of 40 to 60 wh/kg than lead-acid batteries.
- **Nickel-Metal-Hydride Battery** is a modification of Ni-Cd by replacing the cadmium electrode with hydrogen-absorbing alloy. NiMH batteries do have longer lifespans than Ni-Cd batteries (Hasegawa *et al.* 1994). Cadmium is poisonous compared to NiMH batteries, which are more environmentally friendly.
- **Lithium Batteries.** Lithium metal has a considerable advantage to be used as rechargeable batteries because of strong electrochemical potential, lowest density and the energy-to-weight ratio (Tudron *et al.* 2004). In 1912, experiments with

lithium were carried out, and the first set of lithium-based batteries was introduced in 1970. This rechargeable battery was the most stable version and first sold out in 1991 (Goodenough and Park 2013). Lithium batteries electrolyte are made of the solid polymer composite, not a conventional liquid solvent, the electrodes and separators are both laminated to each other (Scrosati and Garche 2010). Due to the solid nature of the electrolyte it is possible for the battery to be encased in a flexible wrapping, rather than a rigid metal casing. Also, this makes it possible for the batteries to be shaped precisely to fit a particular device (Goodenough 2012). Because of their flexibility and compact design, these batteries have an edge to be used for solar-powered aircraft, mobile phones and PDAs.

- **Lithium-Sulphur** (Li-S) battery is an energy storage device with the specific capacity of 600 mAh/g and specific energy density of 2600 wh/kg, theoretically when lithium to the sulphur reaction is fully completed. The highest theoretical energy density is attained by lithium battery (Jeon *et al.* 2002). Interest is geared towards lithium-sulphur battery because of its enormous energy density and affordability of sulphur compared to lithium-ion and lithium-polymer batteries, which have low energy densities. Sulphur to lithium sulphide (Li-S) undergoes complete reaction; this will produce sulphur with a specific capacity of 1675 Ah Kg^1 and an energy density of 2600 Wh/ Kg, which is 3 to 5 times higher than that of Lithium-ion batteries (Zhang 2013). The lithium-sulphur battery is used in Zephyr 7.

ADVANCEMENT IN BATTERY TECHNOLOGY

With the current growth and development of electronic devices, electric vehicle and solar-powered aircraft, there is a high demand for the high energy density of storage systems (Wagner *et al.* 2010). To date, lithium-ion, lithium-polymer, and lithium-sulphur are the rechargeable batteries used for solar-powered aircraft. They have a limited energy density of 250 to 700 Wh/kg, which is insufficient for emerging technology applications (Cairns and Albertus 2010).

Li-air batteries have potential to power various applications in the future, most especially solar-powered aircraft and electric vehicle, mainly because of their great theoretical energy density of 11680 Wh/kg at average, than those of the existing batteries. The Li-air battery high energy density is a remarkable technological breakthrough when compared with the energy density of gasoline as 13000 Wh/kg (Tan *et al.* 2017). It shows that Li-air battery is the key to solar-powered human-crewed aircraft to compete with the conventional aircraft in the nearest future.

Despite the emergence of numerous rechargeable energy storage applications, metal-air batteries are the most vital to improving the energy density capacity, especially lithium-air, aluminium-air, and zinc-air batteries (Lee *et al.* 2011).

MAXIMUM POWER POINT TRACKER (MPPT)

Maximum power point tracker traps the maximum power point (MPP) on the I-V curve to get maximum power from the photovoltaic cell (Ahmed and Salam 2014). PV arrays have non-linear I-V characteristics and output power depends on the condition of the solar irradiance. The maximum power point (MPP) on the I-V curve is the point where power is maximum (Bialasiewicz 2008). MPPT is used to get available maximum power from the PV cell, as the MPP position keeps on fluctuating with changing solar irradiance (Wang *et al.* 2011). The MPPT track the PV operating voltage and current consistent to MPP and locks its, geting the maximum power on PV array to the systems (Kobayashi *et al.* 2003).

The MPPT is formed with a component of power conversion efficiency. Various algorithms for MPPT are available, each with different features and principle of operation (Sahnoun *et al.* 2013)there exist many maximum power point tracking (MPPT. The success of solar-powered aircraft energy is a fundamental issue (Noth 2008) that relies on the MPPT tracking precision and energy tracking factor. For optimum performance of solar-powered aircraft to be attained, the advanced power management system is installed in them, so that photovoltaic cells can be on the maximum power point level, irrespective of whether the high-performance are producing power for propulsion or energy storage mode (Davey 2009).

MPPT methods are categorized into indirect and direct methods (Esram and Chapman 2007). The indirect methods are open circuit and short circuit methods, where PV characteristic is required or based on mathematical relationship. There is no need for meteorology conditions, that is, irradiance and temperature, to track the maximum power point (Park and Yu 2004). The direct methods are P&O, incremental and conductance method and fuzzy logic. These methods follow the MPP under meteorological conditions (Salas *et al.* 2006). MPPTs are also categorized as intelligent and conventional methods. As shown in Table 1, intelligent techniques include Fuzzy logic (FL) and Artificial neural networks (ANN). These MPPT methods are very efficient, with fast response, and are more complicated compared to the conventional techniques that are simpler, cheaper and less efficient, such as P&O and incremental conductance methods (Ram *et al.* 2017; Bouselham *et al.* 2017). Table 1 depicts the major characteristic of MPPT about solar-powered aircraft. The intelligent MPPTs are more suitable in solar-powered application than the conventional type.

Table 1. Major characteristics of MPPT methods (Bhatnagar and Nema 2013).

MPPT method	Complexity	PV array dependent	Direct or indirect	Analog. or digital	Efficiency	Response/ speed	Tracking accuracy	Efficient for partial shading
P&O	Simple	No	Direct	Both	Low	Varies	Medium	No
IncCond	Medium	No	Direct	Digital	Medium	Varies	High	Yes
Open-circuit voltage method	Simple	Yes	Indirect	Both	Low	Medium	Medium	Yes
Short-circuit current method	Simple	Yes	Indirect	Both	Medium	Medium	Medium	Yes
Fuzzy logic	Complex	Yes	Direct	Digital	High	Fast	Very high	No
Neural networks	Complex	Yes	Indirect	Digital	High	Fast	Very high	Yes

PROSPECTS TO THE AVIATION INDUSTRY

The latest technological breakthrough and contribution of researchers in solar-powered aircraft make the sector very promising. The challenges faced by aircraft powered by solar energy for high altitude long endurance (HALE) flight, day and night throughout the year, in all regions of the world is becoming a dream come through in the nearest future. Researchers are working day and night, and grants are provided by both public and private investors for research and development (R&D) to provide sustainable, safe and affordable means of transportation using solar energy entirely as a source of energy.

LATEST TECHNOLOGY TRENDS OF SOLAR-POWERED AIRCRAFT

Latest technology trends in solar-powered aircraft power devices showcase the future image of the aviation industry in a few years to come. Solar-powered aircraft is a system whereby solar energy is used to power the propulsion component and the avionics, sensors and electrical systems of an aircraft. Solar-powered aircrafts can be optimized by lowering the power loading to achieve higher propulsion and aerodynamic efficiencies. The high efficiency of an aircraft is the total sum of the respective component efficiencies of propulsion, aerodynamic and structural components (Cleave 2008).

Nanotechnology provides advanced composite materials for airframe structural developments in aerospace technology applications. This technology is used to produce lighter and stronger materials to withstand aerodynamic and inertial loading with an excellent characteristic of electrical and thermal conductivity.

Smart technologies allow the synchronization of sensors and avionics systems to be portable, lighter, reliable, and to perform better. Also, enable the synchronization to apply to the following components of power device: sensing, control and actuation.

APPLICATIONS OF SOLAR-POWERED AIRCRAFT

Solar-powered aircrafts have the capability for a continuous flight because of the abundant and unlimited quantity of solar energy (Cestino 2006). The legendary durability of aircrafts powered by solar energy is inestimable, with the potential to be used as satellites for very long periods unless it got damaged (Fujita *et al.* 2012) Global Hawk UAV is the first to practically show the advantage of high altitude long endurance flights when it flies over 18.2 m for several days (Stacy *et al.* 2002). Also the Zephyr 7 in 2010 flew continuously for 14 days (Morton *et al.* 2015). Recently, in 2016, solar impulse 2 Bertrand Piccard and Andre Borschberg flew the first long human-crewed solar-powered aircraft approximately 40,000 km in 17 months, around the world flight, completed on July 24, 2016. Solar powered aircraft can fly to attain altitudes higher than 30 km because of solar energy is abundantly available for these aircraft (Hutchinson 2016).

The capability of continuous flight of solar-powered aircraft (UAV) near space makes it possible for application in intelligent surveillance and renaissance (ISR) and relay communication (Najafi 2011), hazard warning, rescue and assessment, agricultural surveillance and decision support systems, and near future planetary atmospheric exploration by NASA (Gómez-Candón *et al.* 2011)which consists of geo-referenced coloured tarps acting as terrestrial targets (TT. Also, the application of human-crewed solar-powered aircraft demonstrated by Solar Impulse 2 looks very bright for the aviation industry.

However, with the current technology development in various power devices of solar powered-aircraft, the design of efficient power device in solar-powered aircraft application is proposed as shown in Fig. 5. The PV cell (GaAs) is used due to its high energy conversion efficiency of 30% to 40%. The MPPT intelligent and smart algorithm (Artificial Neural Network) is chosen because it is very efficient in partial shading and the response/speed is fast. The rechargeable battery (Li-Air) is selected for its possible theoretical high energy density of 11680 Wh/kg, which can sustain long endurance flights in the nearest future.

Different rechargeable batteries and their energy densities applied to aircraft powered by solar energy and the duration of the flight is shown in Fig. 6. Table 2 depicts the application and installation of various PV cells and batteries in solar-powered aircraft. Also, Fig. 7 shows the application of MPPT in solar-powered aircraft.

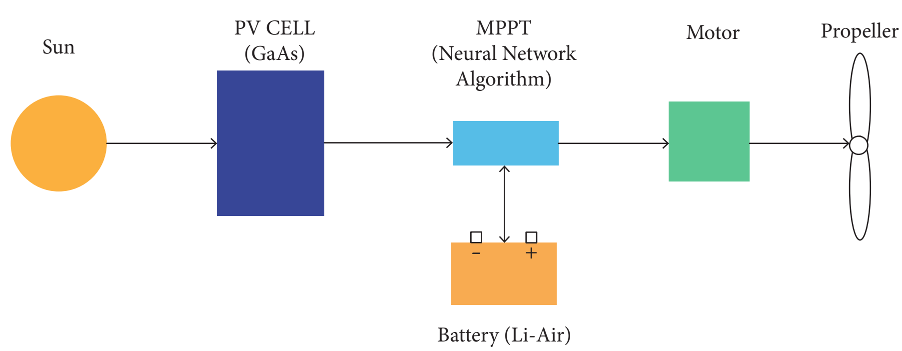

Figure 5. Proposed efficient power device in solar-powered applications.

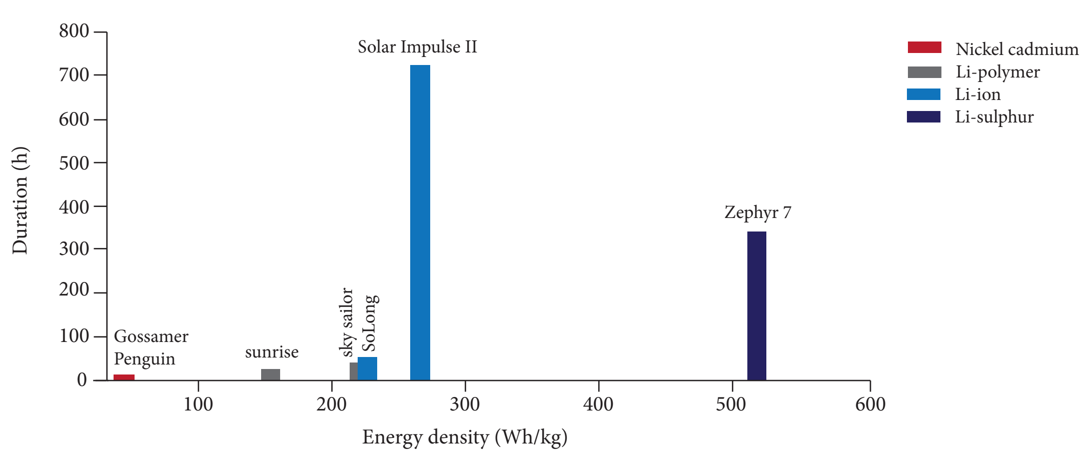

Figure 6. Solar-powered aircraft energy density and flight duration.

Table 2. Application and installation of different PV cells and batteries on solar-powered aircrafts.

Name	Year	Photovoltaic			Battery	
		PV Cell	Efficiency (%)	Power (w)	Battery	Specific energy (Wh/Kg)
Sunrise I (Boucher 1985)	1974	Monocrystalline	11	400	Li-ion polymer	145
Sunrise II (Boucher 1985)	1975	Monocrystalline	16.1	600	Li-ion polymer	145
Gossamer Penguin (MacCready *et al.* 1983)	1983	Monocrystalline	13.2	600	Nickel Cd	50
Solar Challenger (MacCready *et al.* 1983)	1981	Monocrystalline	13	250	Nickel Cd	50
Sky Sailor (Noth *et al.* 2006)	2004	Monocrystalline	18	84	Li-ion polymer	172.8
So-Long (Hartney 2012)	2005	Monocrystalline	18	220	Li-ion	220
Solar Impulse I	2009	Monocrystalline	18	240	Li-ion polymer	240
Zephyr 7 (Davey 2009)	2010	Amorphous Silicon	19		Lithium-sulphur	400-600
Solar Impulse II	2014/2016	Monocrystalline	18	260	Li-ion	260

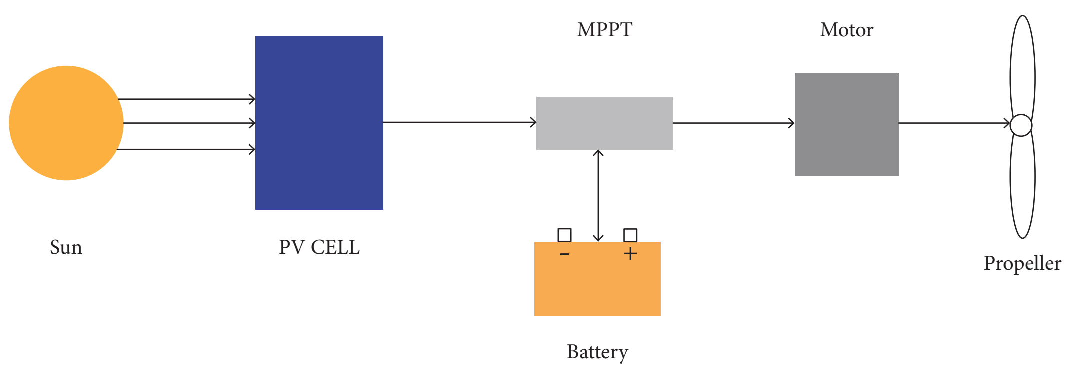

Figure 7. MPPT controller in solar-powered aircraft applications.

CONCLUSION

The solar-powered aircraft power system component comprises photovoltaic cells, rechargeable battery and MPPT. Photovoltaic cells are classified based on materials for solar cell production and are grouped as follows: Crystalline silicon, thin-film, organic/polymer, hybrid PV, and dye-sensitized photovoltaic cell.

The energy density is the most prominent feature to be considered in rechargeable batteries performance. The early stage of rechargeable batteries are low energy density characterizes lead-acid, nickel cadmium, nickel metal-hydride batteries; and later stage are lithium-ion, lithium polymer, and lithium-sulfur, which have an advantage because of their higher energy densities.

The MPPT is the critical component of power conversion efficiency and various algorithms for MPPT are available, each with different features and principles of operation, to ensure the success of solar-powered aircraft design. To get the optimum performance of aircraft powered by solar energy, advanced powered management system is installed.

Emerging technologies provide opportunities shortly for solar aircraft. Thin-film solar cells performance has improved significantly with technologies over time. Multi-junction cells are solar cells with high efficiency ranges, from 40% to 50%. Quantum dots are another solar cell that boosts the bandgap value to harness considerable amount of light coming into the solar spectrum and produces adequate charges from a single photon. All this improved the efficiency of the solar cell.

Regarding battery technology, Li-air batteries have potential to provide energy to different applications, most especially solar-powered aircraft and electric vehicle, primarily because of their high theoretical energy densities, 11680 Wh/kg at average, compared to existing batteries.

With the improvement in technology, an efficient powered device is proposed for solar-powered aircraft application. The capability of continuous flight, high altitude and long endurance of solar-powered aircraft (UAV) in near space makes it possible for its application in intelligent, surveillance and renaissance (ISR) and relay communication, hazard warning, rescue and assessment, agricultural surveillance and decision support systems, and near future planetary atmospheric exploration by NASA.

AUTHORS' CONTRIBUTION

Conceptualization, Safyanu BD, Abdullah MN and Omar Z; Methdology, Safyanu BD, Abdullah MN and Omar Z; Investigation, Safyanu BD and Abdullah MN; Writing – Original Draft, Safyanu BD, Abdullah MN and Omar Z; Writing – Review and Editing, Safyanu BD, Abdullahi MN and Omar Z; Funding Acquisition, Abdullah MN; Resources, Safyanu BD, Abdullah MN and Omar Z; Supervision, Safyanu BD and Abdullah MN.

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