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Research paper

Review of Photovoltaic Cells for Solar-Powered Aircraft Applications

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Abstract

This review paper presents the study of photovoltaic cells for solar-powered aircraft applications. Different PV cells and Maximum Power Point Tracker (MPPTs) are evaluated, and those applicable to solar-powered aircraft are stated. A good irradiance model is developed based on Malaysia as a case study using R.SUN (IET, 2013). The model was developed using the Photovoltaic Geography Information System (PVGIS) of the European Union. PVGIS provide online interactive maps of potentials in Europe, Asia and Africa. The deviation from the tilt angle and geographical location of the flight to follow the cambered airfoil, the camber efficiency is introduced. The cells are designed to dispose of the wings and connected in series to ensure they have a similar orientation. For the flexibility of PV silicon cells for encapsulation on the wing, thin film solar cells is ascertaining suitable to be the best. For the silicon solar cell, because of their brittle nature, two methods were adopted to ensure the silicon solar cell is bend to the airfoil to minimise loss of efficiency.

Keywords: Photovoltaic cells; solar-powered aircraft; MPPT; solar irradiance; and efficiency

1. Introduction

Photovoltaics enable the use of sunlight in a clean, ever-lasting, and the highly versatile way [1]. The quest for the search for alternative and sustainable energy-aware from fossil fuel, photovoltaic cell is the best option as sunlight is abundant and inexhaustible. Due to technology advancement and severe environmental hazard and awareness for clean energy, PV module industry is rising at almost 25% or more every year [2]. The solar energy was used in the early 1950s and 1960s to power the earth-orbiting satellites[3].

Solar powered aircraft is the technology that the concept started long ago in 1974 by Robert J. Boucher, and the technology is still promising with a lot of research breakthrough [4]. The inexhaustible source of solar radiation makes the technology affordability, save and sustainable and clean means of transportation, and the aircraft to exhibit prospective for high altitude and long endurance (HALE) flight [5]. Solar powered aircraft is categorized into two groups; unmanned and manned. The unmanned is used for high altitude communication platforms, border surveillance, forest firefighter and power initiation. The latter is still on research stage and test flight, with the hope to be used for the civilian and military mission. A typical example is a solar impulse 2 [6].

The solar-powered aircraft design is power by photovoltaic cells as the main source of energy. Maximum power point tracker is used to get the maximum power from the PV [7]. The PV cell is installed on the wing, which converts solar radiation to electrical energy to power the aircraft systems. The rechargeable battery is mounted on the fuselage, and the battery is charging at daytime when the solar radiation is optimal and discharge at night time [8]. The solar-powered aircraft faced challenges of energy to satisfy the requirement of the mission for high altitude and long endurance [9]. The capability of the conversion efficiency of solar irradiance to electrical energy by the solar cell is limited. The solar-powered aircraft is crippled with various challenges of energy collection from the PV to power a particular mission. The energy collection to powered solar-powered aircraft faced challenges that bother, on the orientation and inclination of the solar cell area, the latitude, the time of the year and the time of the day [10]. Also, the altitude and the weather is very imperative in the collection of the solar energy [11]. Other problems encountered by solar-powered aircraft includes; temperature of the solar cells, weight, arrangement type on the wing, flexibility for encapsulation on the wings and deviance from the angle tilt of the PV cells.

All of the above-highlighted problems of the solar-powered aircraft derived from the PV cells will be analysed in this paper, with the aim to improve the conversion efficiency.

1.2 Transition of Solar-Powered Aircraft

Sunrise I, was the first solar-powered aircraft in 1974, design and constructed by Robert J. Boucher, installed with 4096 PV cells of monocrystalline with 450W of power and 11% efficiency [4]. Gossamer Penguin was the first ever manned aircraft that was built in 1980 by Dr Paul MacCready and also, designed Solar Challenger an unmanned solar aircraft [12]. Alan Cocconi designed SoLong in 2005 with SunPower A300 monocrystalline solar cell, which generates 225W [11]. In 2008 Sky-sailor solar-powered aircraft by Andre Noth powered by monocrystalline solar cell with duration of 27 hours [13] In 2010 Zephyr 7 was the first unmanned solar aircraft to fly nonstop for 72hours, had installed with amorphous silicon with 19% efficiency [14]. The Solar Impulse 1, in 2009 is installed with monocrystalline solar cells of 11,628 with 18% efficiency and 84W [15]. Solar Impulse II, is also, the first manned solar aircraft that flew around the world from 2014 to 2016 and installed with a monocrystalline of 17,248 solar cell [6].

2. Photovoltaic Solar Cell

A P-N junction display a voltage and current complex link in the solar cell [16]. The solar irradiance on the cell produces voltage and current which display the intricate connection between insolation and output power [17]. On a sunny day with bright light, the solar cell internment slows moving low energy electrons [18]. Low insolation produces high power while vice-versa generate low power, due to the saturation of cells, and this limits the number of free electrons and their mobility significantly [19].
Fig.1 shows the IV characteristic of the complex link between the voltage and current relationship. The open voltage is the voltage across the terminal in an open circuit while the short circuit current is the current passing through when the wire is short circuit while the voltage is zero. The intricate relationship of the I-V curve at the point where the maximum power of Voltage (V_{MP}) and the maximum current (I_{MP}) intersect is the maximum power. This is the point that the solar-powered aircraft derives its maximum power from the solar radiation.

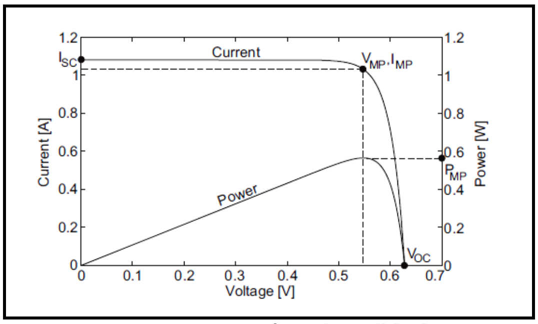

Fig.1: I-V Curve of a Solar Cell [20]

2.1. Classification of Photovoltaic Cell

Photovoltaic solar cells are classified on the constituent for the production of the solar cell. The classification is as follows; Crystalline Silicon, Thin film, Organic/polymer, Hybrid PV and Dye-Sensitized photovoltaic cell [21]. Fig. 2 shows the classification of PV cell based on PV material. The PV cell energy conversion is theoretically related but differs in material and production [22]

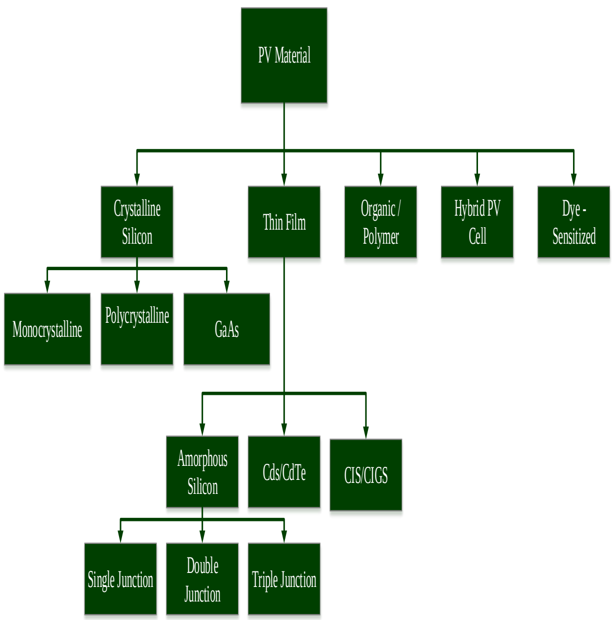

Fig.2: Classification of photovoltaic cell based on PV material [21].

2.1.1. Crystalline Material

Crystalline material PV cell comprises mono-crystalline, poly-crystalline and gallium arsenide (GaAs) cell. Most of the solar-powered aircraft used crystalline silicon as depicted in Table 1, which shows the different types of solar-powered by silicon PV cells and their performance.

2.1.2. Thin Film PV Cell

This type of PV cells is manufactured directly by using thin film semiconductor layer of PV material printed or sprayed on a glass, metal or plastic foil substrate [23]. The PV cell thickness is smaller when compared to cut crystalline cell. The manufacturing process of 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 compared to crystalline cells [24], and they have low cell conversion efficiency due to lack of crystalline structure, requiring more substantial sized cells. *Cadmium Telluride, Amorphous Silicon, and Copper Indium di-Selenide or CIS* these are types of thin PV cells.

2.1.3. Organic and Polymer Cells

Due to the following reasons; physical flexibility, disposable, and cost-efficient of the material attract the interest of the researchers [25]. The polymers have properties to replace silicon PV modules due to cost and weight factors in the nearest future [26]. The output voltage of organic material increased by producing of broad absorption band material [27].

2.1.4. Hybrid Solar Cell

The fusion of crystalline silicon with non-crystalline silicon produces a hybrid solar cell. The Assumption of amorphous silicon with crystalline silicon produce a high-performance ratio of the solar cell [28].

2.1.5. Dye-Sensitized Solar Cell

A typical solar cell by the photo-sensitised anode and an electrolyte produce the semiconductor film [29]. The dye-sensitised solar cell is a useful technology compare to the existing ones [30].

2.2. Photovoltaic Solar Cell Development

Over the year's thin-film solar cell technologies have improved with high energy conversion efficiency. The improve application of thin-film solar cells is because of their ability at higher temperatures to produce high efficiency than crystalline silicon cells that display high efficiency at low temperature [31]. They can translate much larger light frequencies than any other solar cell, retain their efficiency at high temperature and exhibit high-efficiency greater than 40%. With the recent technology, the efficiency in the next ten years can get up to 50% [32]. Quantum dots technology can improve the efficiency of solar cells by more than 66%. This is achieved by increasing the bandgap of solar cells [33].
Nanomaterials such as Nano-wires and Nano-particles have an advantage in applications than photovoltaic devices. The Nanometre size objects have a huge interfacial area because of the large surface area per unit volume. The Nano size creates a quantum confinement effect which provides an opportunity to design a Nano-materials with different band gaps as shown in Fig. 3. Polychoral carbon nanotubes with a solar cell. Just like quantum dots, this can improve the band gap and subsequently increase the efficiency, to meet high-efficiency requirements.

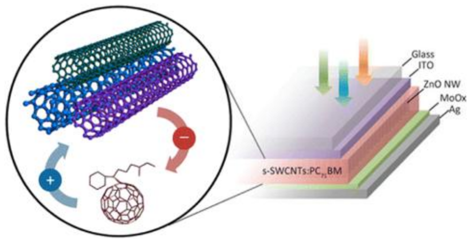

Fig. 3 Polychoral carbon nanotubes with a solar cell. [34]

The technology can be used to produce the airframe of the aircraft not only limited to the solar cell. The thin film carbon Nano-tubes and Nano-fibers as shown in Fig. 4. They have been magnetically united, to be 10 times lighter and equally 500 times robust than steel [35]. They conduct electricity alike to silicon or copper and diffuse heat similar to steel and brass. This technology shows potentials to improve the solar cell efficiency and make it affordable [17].

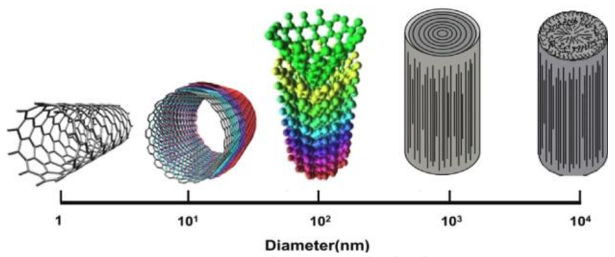

Fig 4: Carbon nanotube [35]

3. Maximum Power Point Tracker (MPPT)

Maximum power point tracker is an electronic means that tracks the maximum power point on the I-V curve, to get maximum power from the photovoltaic cell [36] [18]. MPPT is a device that catches the optimal power from the PV, as the position of MPP fluctuates through variation in atmospheric conditions [37]. The MPPT locates the PV voltage and current consistent with MPP and locks its and abstract the optimal power from the PV array to the systems [38].
The MPPT is the critical component of power conversion efficiency and various algorithm for MPPT are available each with different features and principle of operation. The success of solar-powered aircraft energy is a fundamental issue [13], so, the MPPT pursuing accuracy and energy pursuing factor is very imperative. The optimum performance of solar-powered aircraft to be attained, advanced powered management system is installed in the aircraft so that photovoltaic cells can operate at the highest power point level if the cells are providing the power or it's from the energy storage [39].
MPPT methods that are usually used for the solar-powered application are intelligent techniques which include; Fuzzy logic (FL) and Artificial Neural Network (ANN). These methods are very efficient, with fast response, and more complicated [19] [40].

4. Irradiance Model

The irradiance is a function of latitude, time, plane orientation, weather conditions and albedo the ground reflection. A model is developed in Malaysia as a case study using R.SUN (IET, 2013). The model was developed using the Photovoltaic Geography Information System (PVGIS) of the European Union. PVGIS provide online interactive maps of potentials in Europe, Asia and Africa. Fig 5 shows a solar radiation map, and Fig.6 shows the daily solar radiation in Malaysia courtesy of (PVGIS). The trigonometric model will be formulated by using, the maximum irradiance, the efficiency of the weather and the duration of the day for various conditions; global, direct, diffuse and clear-sky (assumed value of 1 is used for clear-sky) parameters that can be easily interpreted in Fig. 5. shows the daily solar radiation. The daily solar energy per square meter can be easily calculated using equation (1).

$$E_{daydensity} = \frac{I_{max} T_{day}}{\pi / 2} \eta_{wthr} \quad (1)$$

$E_{daydensity}$ - Daily solar energy per square meter

I_{max} - Maximum irradiance, T_{day} - Time of the day

η_{wthr} - The efficiency of the weather

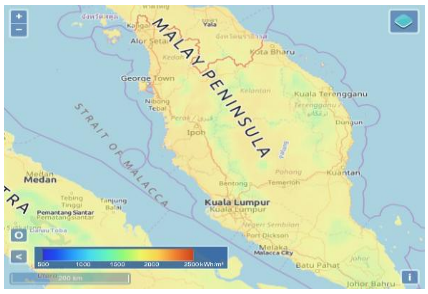

Fig. 5: Solar radiation map of Malaysia.

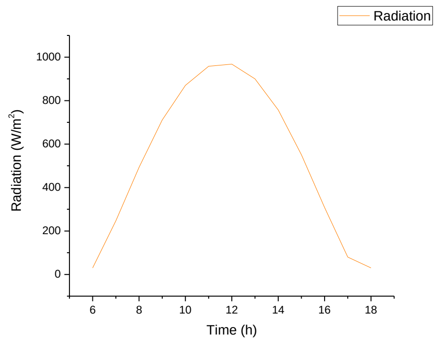

Fig.6: Daily solar radiation of Malaysia

5. Deviation from Tilt Angle and Geographical Location of the Flight

The daily solar energy is the function of the total electric energy which can be acquired by the product of the daily solar energy per square meter in equation (2) with the solar cells surface area and with its efficiency and also the efficiencies of the weather MPPT and cambered. The cambered efficiency is considered because the solar cells are arranged on the cambered airfoil shape. As the cells are interconnected, the cell that absorbs low solar radiation reduces the current for all the others. Fig. 7 captured the scenario, that shows a different incidence angle on the solar cells for an airfoil wing from morning to nightfall, the first cell, on the airfoil of has the minimum angle of elevation θ_1 capable of penalizing other cells.
Due to the above issues, the cells are designed to laid on the wings and connected in series to ensure they have a similar orientation. Early studies have shown that the above problem decreases the energy by almost 10% during a whole day in central Europe. A new efficiency (camber) that is greater than 90% is introduced. Therefore, the daily electrical energy is:

$$E_{electot} = \frac{I_{max} T_{day}}{\pi/2} A_{sc}\, \eta_{wthr}\, \eta_{sc}\, \eta_{cbr}\, \eta_{mppt} \qquad (2)$$

$E_{electot}$ - Daily electrical energy; A_{sc} - Solar cell area

η_{sc} - Solar cell efficiency, η_{cbr} - Camber efficiency

η_{mppt} - MPPT efficiency

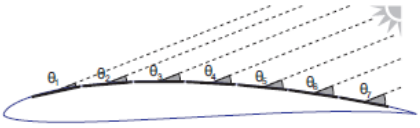

Fig. 7: Deviation of incidence angle on the solar cells for a cambered wing at sunrise or sunset [13].

6. The flexibility of PV for Encapsulation on the Wing

Encapsulation of PV cells on the wing of solar-powered aircraft to bend on the airfoil is very important for PV cell conversion efficiency. To ensure PV cell is encapsulated on solar-powered aircraft and bent on the airfoil effectively, the PV cell must be flexible. Thin-film PV cells are the perfect type of solar cells to encapsulate on the solar-powered and bent to the airfoil. But most of the solar-powered aircraft used crystalline silicon photovoltaic solar cell as shown in **Table 1** that depict the different types of aircraft powered by crystalline silicon. The problem with the encapsulation of the crystalline materials are brittle, and cannot be shaped to the airfoil to retain high aerodynamic efficiency.

Table 1: The Different Type of Aircraft Powered by Crystalline Silicon and Performance

Aircraft	Year	Solar cell	Conversion efficiency (%)	Output power (w)
Zephyr7	2010	Amorphous silicon	19	-
Xihe	2009	-	16	-
Solar Impulse HB-SIA	2009	Monocrystalline 10,748 cells	18	6000
So-Long	2005	Monocrystalline silicon	-	225
Heliplat	Start from 2004	Monocrystalline silicon	22	1500
Skysailor	2004	Monocrystalline REW32 216	16-18	84
Helios	2001	Sunpower monocrystalline 62000	16	-
Pathfinder	1997	-	14.5	225
Gossamer penguin	1981	Monocrystalline silicon 3920 (2240(2×4cm), 700 (2×6cm), 980(2.4×6.2cm))	13.2	540
Sunrise II	1975	Monocrystalline silicon 1120 (2×4cm)	16.1	580
Sunrise I	1974	Monocrystalline silicon	11	400

(-) Means data not available

6.1 Encapsulation of Silicon Photovoltaic Solar Cell

The encapsulation of crystalline silicon solar cell two methods were adopted. The first is to fold the solar array to cover the airfoil shape. Crystalline Silicon cell cannot be folded in a small range because of the elasticity of the solar cell; adhesiveness skin is used to fit the solar cell on the airfoil [41] as shown in Fig. 8 Which is the method to install PV Cell on the airfoil shape. Although this method is not efficient because the exact airfoil shape is not met due to lack of elasticity of the solar cells and the procedure used in the production, which affect the aerodynamic efficiency.

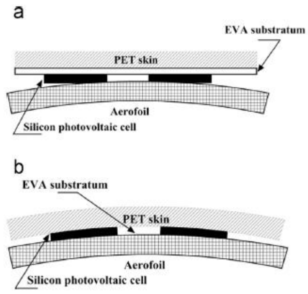

Fig. 8: Method to install on PV Cell on the airfoil shape.

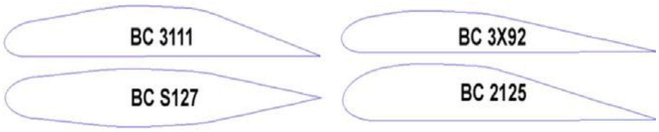

Fig. 9: The flat-panelled airfoil special designed for solar-powered aircraft [42]

The second is to apply a flat-panelled airfoil, the example of the airfoil is shown in Fig. 8 above. And the photovoltaic cells can be installed on the wing without bending, as shown in Fig. 10 Solar-powered aircraft PV installation (Helios prototype). This method, eliminate any losses of efficiency due to bending during encapsulation, and the loss of efficiency to irradiance differences over a curved solar array is minimised [42]. However, the bottom of the airfoils if is flat, can be used to installing more solar cells to collect earth albedo radiation for more solar energy.

Fig. 10: Solar-powered aircraft PV installation (Helios prototype) [42].

7. Conclusion

Photovoltaic solar cells are classified for materials used in the production of the solar cell. The classification is as follows; Crystalline Silicon, Thin film, Organic/polymer, Hybrid PV and Dye-Sensitized photovoltaic cell. Quantum dots technology can improve the efficiency of solar cells by more than 66%. This is achieved by increasing the bandgap of solar cells. Nanomaterials such as Nano-wires and Nano-particles have an advantage in applications than photovoltaic devices. The technology can be used to produce the airframe of the aircraft not only limited to the solar cell. The MPPT is the critical component of power conversion efficiency and various algorithm for MPPT are available each with different features and principle of operation. A good irradiance model is very imperative, and for the success of solar-powered aircraft, for this reason, a model is developed based on Malaysia as a case study, using R.SUN (IET, 2013). The camber efficiency is introduced to mitigate the losses that are associated with variation of the solar radiation related to the camber shape of the airfoil. Due to the above issues, the cells are designed to dispose of the wings and connected in series to ensure they have a similar orientation. For encapsulation of crystalline silicone, two methods were adopted.

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