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The journal is published 4 times a year and contains publications in the following main areas:

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CONTEXT / MUNDARIJA

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Analysis of solar cells can be used in the design of solar-powered UAV

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Abstract: Interest in solar-powered unmanned aerial vehicles (UAV) is increasing today due to their ability to fly for long periods of time. Solar cells play an important role in their long-term flight, and the right choice of solar cell technology has a significant impact on the performance and efficiency of these solar-powered UAVs. This article analyses various solar cells for solar powered UAVs, considering their specifications such as efficiency, power output, weight, etc., and other factors such as installation, durability, and cost effectiveness. Various types of solar cells, including silicon-based, thin-film, multi-junction, and emerging technologies, are evaluated based on their suitability for solar-powered UAV applications and at the end, conclusions are presented on the selection of the most optimal solar cell that can be used in the design of such UAVs.

Keywords: Solar-powered, solar cell, photovoltaic, long-endurance

1. Introduction

When it comes to the design and development of solar-powered UAVs (Unmanned Aerial Vehicles), selecting the right type of solar cells is critical for maximizing efficiency, power output, and integration with the UAV’s design. Solar energy is considered sustainable energy and the main goal of using it in flight is to achieve longer flight endurance, and the main means to achieve this is the use of solar cells in drone construction and design in general. Of course, each solar panel UAV is different depending on the field of application and the mission it performs, which means that in this case their flight duration requirements will be different as well as the actual flight durations. Furthermore, the use of solar cells alone may not be sufficient to achieve the intended flight duration. There are other factors to consider, such as drone size, weight, construction, especially the integration of solar cells with the wing, drone mission, weather (available sunlight, etc.), solar cells and their type, etc.

The following is an analysis of the solar cells that can be used in the design of a solar panel drone through the method of reviewing the available literature and sources, presenting the specifications, data of the various solar cells, the solar cells used in the drones reported so far and the results they have shown, as well as the above taking into account the listed factors, solar cells are divided into groups.

1.1. Silicon-based solar cells.

Silicon is a common and inexpensive material [1], and approximately 85% of photovoltaic cells on the market are solar cells made of this material [2]. Also, most of the solar-powered UAVs developed so far, for example, Switzerland's AtlantikSolar 2, China's Mini-Phantom UAV, used monocrystalline solar cells made of this material. Solar cells made of this material can be divided into 3 types (figure 1):

- monocrystalline silicon (mono-Si), (or single-crystalline);
- polycrystalline or polysilicon (p-Si) and multi-crystalline silicon (mc-Si);
- amorphous (a-Si), (or thin-film cell).

Monocrystalline solar cells.

Consisting of a single continuous crystal structure, they are highly efficient and have a high power-to-weight ratio. They typically offer a high efficiency rating of 15-20% [3], with even later brands slightly exceeding 22%, and can perform well in low sunlight conditions and have a longer lifespan. Often these solar cells can be more expensive (compared to polycrystalline for example) and less flexible, which can be considered a disadvantage when designing solar-powered UAVs that require a panel composed of flexible or lightweight solar cells.

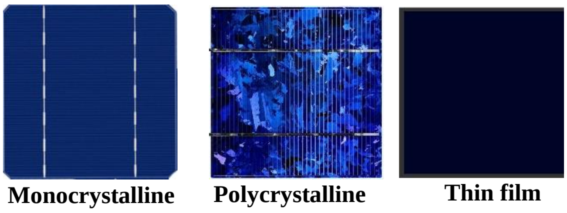

Figure 1. Silicon-based and thin film solar cells

Another important factor is the ease of finding and buying these cells. For example, it can be seen their existence and wide spread even when looking at various Internet online trading markets. Monocrystalline solar cells include brands such as Sunpower C60, Sunpower A300, Sunpower Maxeon Gen 6, etc., that can be used in the design of solar UAVs. However, for example, solar cells of this type were used in solar UAV projects such as MARAAL, AtlantikSolar, SoLong, Sunsailor 1, Sunsailor 2 [5] and Solar Impulse 2 aircraft. Table 1 provides specification information for some monocrystalline solar cells, and Fig. 2 shows a typical I-V (current-voltage) curve diagram of the Sunpower C60.

Polycrystalline solar cells.

Polycrystalline solar cells, also known as multicrystalline silicon cells, are a popular type of photovoltaic technology used to convert sunlight into electricity. Unlike their monocrystalline counterparts, which are made from single crystals of silicon, polycrystalline cells are composed of multiple silicon crystals.

The production of polycrystalline solar cells begins with silicon that is melted and then poured into molds to form

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blocks known as ingots. These ingots are then sliced into thin wafers, which are the basis for solar cells. The process is less complex than the creation of monocrystalline cells, which involves pulling a single crystal from molten silicon.

Polycrystalline solar cells are characterized by their distinct blueish hue and the visible grainy texture on their surface. This texture results from the multiple silicon crystals within the cell. One of the primary advantages of polycrystalline cells is their lower production cost compared to monocrystalline cells. This is largely due to the simpler manufacturing process and reduced silicon waste.

Table 1

General and electrical specifications of two monocrystalline solar cells

Sunpower C60				
Dimensions (Length x width)	***Thickness***		***Weight***	***Efficiency***
125 mm x 125 mm (nominal)	(165µm ± 40µm)		-	~ 22.5 %
Rated power Pmpp (Wp)	***Voltage at maximum power point Vmpp (V)***	***Current of module at maximum power point Impp (A)***	***Open-Circuit Voltage Voc (V)***	***Short-Circuit Current Isc (A)***
3.42	0.582	5.93	0.687	6.28
Sunpower A300				
Dimensions (Length x width)	***Thickness***		***Weight***	***Efficiency***
125 mm x 125 mm (nominal)	270 µm ± 40 µm		-	~ 21.5 %
Rated power Pmpp (Wp)	***Voltage at maximum power point Vmpp (V)***	***Current of module at maximum power point Impp (A)***	***Open-Circuit Voltage Voc (V)***	***Short-Circuit Current Isc (A)***
3.1	0.560	5.54	0.670	5.9

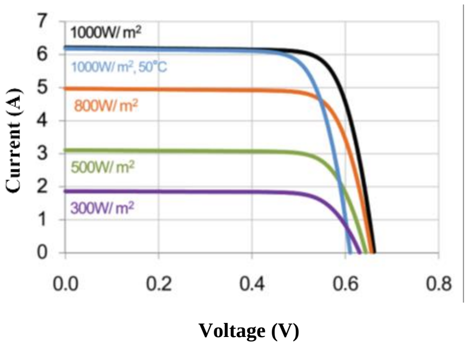


Figure 2. Sunpower C60 Typical I-V Curve

In terms of efficiency, polycrystalline solar cells typically have a lower conversion efficiency than monocrystalline cells. This means that polycrystalline cells generally produce less power per square meter of panel compared to their monocrystalline counterparts. However, advancements in technology and manufacturing processes are continually improving their performance. The efficiency rating of polycrystalline panels typically ranges from 13% to 16%. Even though it is only a little percentage point less than monocrystalline panels, when multiplied over numerous solar panels, the difference can add up [9].

Amorphous Silicon cells.

Actually, this kind of photovoltaic cell can be included in the thin film group. This kind of thin-film photovoltaic cell utilizes non-crystalline silicon. Contrasted to crystalline silicon utilized in typical silicon solar cells, amorphous silicon is applied in thin layers on a substrate. Although it is more flexible and inexpensive to produce than crystalline silicon cells, its efficiency is usually lower. Its low photoelectric conversion efficiency is its biggest flaw. Currently, the efficiency ranges from 4-8% in commercial modules to about 13.5% in laboratories alone [10]. In addition to the characteristics of this solar cell, it is lightweight.

1.2. Thin-Film Solar Cells.

Thin-film photovoltaic cells (figure 1) represent a category of photovoltaic technology designed to convert sunlight into electricity with a streamlined and flexible approach. Unlike traditional silicon-based solar cells, which use a solid, crystalline structure, thin-film cells are composed of layers of photovoltaic material that are only a few micrometres thick. This design enables the production of lightweight and flexible panels.

The core advantage of thin-film technology lies in its versatility and manufacturing efficiency. These cells can be deposited on a variety of substrates, including glass, plastic, or metal, letting them to be combined into various applications.

Thin-film photovoltaic cells make use of various materials to catch sunlight, such as cadmium telluride (CdTe), amorphous silicon (a-Si), or copper indium gallium selenide (CIGS). Each material has unique properties that influence the cell's efficiency, durability, and production cost. For instance, CdTe cells are known for their low production cost and relatively high efficiency in converting sunlight into electricity, while CIGS cells offer high efficiency and flexibility but are more complex to manufacture.

The primary challenge with thin-film solar cells is their efficiency compared to traditional silicon-based cells. While thin-film cells generally offer lower efficiency, advancements in technology and manufacturing processes are continuously improving their performance and making them more competitive in the renewable energy market.

Cadmium telluride solar cells

Cadmium telluride solar cells are photovoltaic devices that use a thin layer of cadmium telluride (CdTe) to generate electricity from light. In contrast to crystalline silicon photovoltaic technology, CdTe solar cells use a thin film of semiconductor, a smaller amount, to convert absorbed light energy into electrons. Despite having lower efficiency than crystalline silicon devices, CdTe solar cells can be produced at a lower cost, and the technology has the potential to outperform silicon in terms of cost per installed kilowatt. Even though thin film technologies only make up a small portion of the solar device market, this industry is predicted to expand quickly due to the strong interest in creating novel methods of manufacture that may allow for economies of scale.

Amorphous silicon, which was randomly deposited onto a substrate (as opposed to the regular crystal lattice found in wafer crystals) was the first thin film technology to be invented. There were a few issues with this technology: the cells were inefficient, and the process of depositing silicon onto the substrate was expensive and time-consuming. Because of its excellent solar spectrum matching and 1.4

electron volt band gap - the energy required to drive an electron from its atom into a condition where it may flow freely - CdTe thin film technology is approximately 11% more efficient than amorphous silicon.

Because the CdTe thin film is a high-throughput technique and can be deposited onto the substrate rapidly, it is also far more suitable for mass manufacturing. A p-doped layer of cadmium telluride, referred to as the “absorber”, sits atop an n-doped cadmium sulphide junction, or “window layer,” in each cell. Cadmium sulphide is covered by a transparent conductive front contact, and the CdTe is in contact with a conductive rear surface substrate. Fig. 3 show different layers of CdTe/CdS thin film photovoltaic sells.

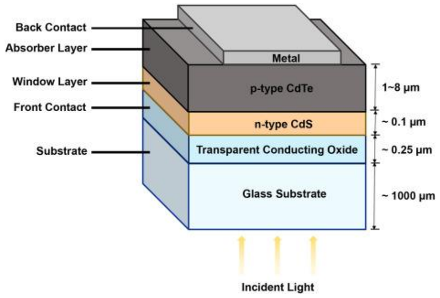


Figure 3. Structural layers of CdTe/CdS solar cells

Since cadmium is a cumulative poison, the electronics industry has taken steps to try and remove elemental cadmium from personal devices despite its potential. Cadmium has been effectively removed from electronic equipment in Europe thanks to the Restriction of Hazardous Substances (RoHS) regulations, which were implemented in response to health concerns. Cadmium not only poses a health concern to consumers, but it also poses a risk to miners during the raw material extraction process, workers involved in the processing of the material, and disposal workers during the end of their lives.

Proponents claim that cadmium in the form of a thin film solar cell is more stable and less soluble than in other electronics and that there would be little risk to health and the environment, as the alloys are encapsulated within the modules. However, there have been concerns regarding cadmium leaching from broken modules. Additionally, although it has been promoted that closed-loop recycling would address any concerns over end-of-life disposal, critics highlight that even closed-loop recycling systems do not recover everything [11, 18].

Copper indium gallium selenide solar cells

Copper indium gallium selenide (CIGS) solar cells are a prominent type of thin-film photovoltaic technology known for their efficiency and versatility in converting sunlight into electrical energy. These cells are composed of a compound semiconductor material, which is primarily made up of copper (Cu), indium (In), gallium (Ga), and selenium (Se). The unique properties of these materials enable CIGS solar cells to offer several advantages over traditional silicon-based solar cells.

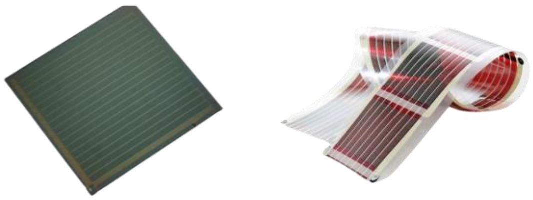
The deposition of the CIGS layer is usually achieved through techniques such as sputtering, co-evaporation, or chemical vapor deposition (CVD). These methods allow for precise control over the composition and thickness of the CIGS layer, which is crucial for optimizing the cell’s performance.

CIGS solar cells are renowned for their high efficiency in converting sunlight into electricity. They typically achieve efficiencies of around 15-20% in commercial applications, though laboratory prototypes have reached efficiencies exceeding 23%. This level of performance is competitive with, and in some cases surpasses, that of traditional silicon-based solar cells [11].

One of the key factors contributing to the high efficiency of CIGS cells is their direct bandgap, which is ideal for absorbing a broad spectrum of sunlight. This characteristic allows CIGS cells to capture more energy from sunlight compared to materials with an indirect bandgap, such as silicon.

1.3. Emerging and Specialized Solar Cells

Recent advancements in solar cell research have introduced promising alternatives for UAVs. Perovskite solar cells have garnered attention for their potential to achieve high efficiencies comparable to silicon-based cells while offering lower manufacturing costs and the ability to be fabricated on flexible substrates. Organic photovoltaics (OPVs) present another avenue with their lightweight and flexible nature, although current efficiencies are lower than those of silicon-based and perovskite cells. Continued research and development efforts aim to improve the efficiency, stability, and scalability of these emerging technologies for UAV applications. Figure 5 shows perovskite and organic photovoltaic solar cells.



a) Perovskite solar cell b) Organic photovoltaic cells

Figure 5. General view of Perovskite and Organic solar cells

Perovskite solar cells

The core of a perovskite solar cell is the absorption layer, which is made up of a material with a crystal structure that absorbs light and partially converts it into a stream of electrical charges that we refer to as electrons (positively charged) and holes (negatively charged). The perovskite layer is surrounded at both the top and bottom by layers of transport material that only permit one of the two types of charges to pass through: holes or electrons. This charge transport creates a voltage difference, with the layer that accepts holes becoming positive and the layer that accepts electrons becoming negative. The transport layers are covered with conductive electrodes to allow the electric current to flow correctly.

Perovskite solar cells can be applied as extremely thin layers to a variety of substrates, such as glass, foil, or another solar cell, because at least one of these electrodes - the front of the photovoltaic cell - is transparent and the stack of layers is only a thousandth of a millimetre thick [15].

Organic photovoltaic cells

The newest development in solar cell technology, organic solar cells, also referred to as organic photovoltaic cells (OPV), are attracting the interest of business experts. This is mostly because of their excellent performance, their unparalleled capacity to absorb solar energy, and the remarkable adaptability of the technology.

In contrast to conventional crystalline solar cells, which employ silicon as an absorber, organic solar cells use an organic electronics and polymer or small molecule cell composed of carbon-based materials. This makes it possible to create a thinly-film solar cell that is incredibly flexible, light, and thin. In comparison with usual photovoltaic cells, organic photovoltaic cells have a far wider coverage area and are far more robust due to their unique device structure.

The procedure for producing monocrystalline and polycrystalline silicon solar cells is the same for organic solar cells. The process via which all of these kinds of photovoltaic cells generate electricity is called the photovoltaic effect. The direct atomic-level conversion of light into electricity is known as the photovoltaic effect. The solar cell absorbs light in the form of tiny energy bundles called photons as the initial step in this process. After the photons are knocked by the solar cell, the electrons escape the semiconducting material and are picked up by electron acceptors. When the electrons are free to move around the solar cell, they can pass through charge carriers and produce an electrical current. After that, that electric current is collected and distributed throughout any house.

The photovoltaic mechanism works similarly for silicon and organic solar cells. The semiconducting substance used in each solar cell is the only variation. Organic solar cells use a carbon-based substance as a semiconductor, as opposed to conventional solar cells, which use silicon [16].

1.4. Multi-junction solar cells

In comparison with single-junction photovoltaic cells, multi-junction photovoltaic cells are more effective in converting sunlight into electricity because they can absorb different wavelengths of incoming sunlight by using different layers. Multi-junction photovoltaic cells have the potential to be many times more efficient than usual photovoltaic cells, but they are not currently viable or commercially available due to high production costs and ongoing research and development. Tandem solar cells, of which multi-junction solar cells are a kind, are constructed from stacked materials that have been specially designed to absorb various sun frequencies.

Semiconductor material, primarily silicon in crystalline solar cells, is used to make solar cells. A solar cell's two layers are typically an n-type, which has a high electron concentration, and a p-type, which has a comparatively low electron concentration. Electrons move from the n-type layer to the second portion when sunlight strikes it, creating an electrical current that may be recorded and used to generate power. Because it includes a single boundary, or p-n junction, between the n-type and p-type layers, this type of photovoltaic cell is referred to as a single-junction photovoltaic cell. In solar cells, electrical currents travel across these p-n junctions.

It is not possible to develop multi-junction photovoltaic cells using silicon as a semiconductor. Rather, distinct layers of semiconductors that react to various wavelengths of incoming sunlight are created using materials such as germanium (Ge), gallium indium phosphide (GaInP), and indium gallium arsenide (InGaAs) [17]. Below are the specifications (table 2) of Spectrolab's NeXt Triple Junction (XTJ) solar cell (figure 6), an example of multi-junction photovoltaic cell.

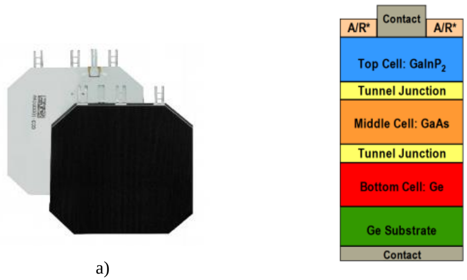
2. Analyses and results

Considering the above, the following analysis and results can be summarized:

1) Silicon-Based Solar Cells:

Advantages:

- High Efficiency: Monocrystalline silicon cells offer efficiencies up to 20-25%, making them suitable for applications requiring high power output in limited space.
- Mature Technology: Extensive research and development have optimized their performance and reduced costs.
- Durability: Silicon cells have a proven track record of long-term reliability and durability.
- Limitations:
- Weight and Rigidity: Silicon cells are relatively heavy and rigid, which may affect the aerodynamics and payload capacity of drones.
- Efficiency Degradation: Performance can degrade over time, particularly in high-temperature environments.



a)

*A/R: Anti-Reflective Coating

b)

Figure 6. View (a) and structure (b) of NeXt Triple Junction (XTJ) solar cell

Table 2

Specifications of NeXt Triple Junction (XTJ) solar cell

<table>
<tr><th colspan="5">NeXt Triple Junction (XTJ)</th></tr>
<tr><th colspan="2">Dimensions</th><th>Thickness</th><th>Weight</th><th>Efficiency</th></tr>
<tr><td colspan="2">26.62 cm² and 59.65 cm²</td><td>140 µm Ge wafer thickness</td><td>84 mg/ cm²</td><td>29.5%</td></tr>
<tr><td rowspan="2">AM0
(135.3 mW/cm²)
28°C, Bare Cell</td><td>Voltage at maximum power point Vmpp</td><td>Current of module at maximum power point Impp</td><td>Open-Circuit Voltage Voc</td><td>Short-Circuit Current Isc</td></tr>
<tr><td>2.348 V</td><td>17.02 mA/cm²</td><td>2.633 V</td><td>17.76 mA/cm²</td></tr>
</table>

2) Thin-Film Solar Cells:

Advantages:

- Lightweight and Flexible: Thin-film cells are lighter and more flexible compared to silicon-based cells, making them ideal for integration into the curved surfaces of drone wings.
- Low Production Costs: The manufacturing process of thin-film cells is less expensive, contributing to lower costs per watt of power generated.
- Performance in Low Light: Some thin-film technologies perform better in low-light conditions and diffuse sunlight.

Limitations:

- Lower Efficiency: Thin-film cells typically have lower efficiencies, ranging from 10-15%, which may necessitate larger surface areas for the same power output.

- Shorter Lifespan: These cells may experience faster degradation over time, potentially reducing their effectiveness and reliability in long-term drone operations.

3) Emerging and Specialized Solar Cells:

Advantages:

- High Efficiency Potential: Perovskite cells have demonstrated efficiencies exceeding 25% in laboratory settings, with the potential for further improvements.
- Flexibility and Lightweight: Organic and perovskite cells are highly flexible and can be integrated into various substrates, including lightweight and curved surfaces.
- Cost-Effective Manufacturing: The use of solution-based processing techniques can potentially reduce production costs.

Limitations:

- Stability and Durability: Many emerging technologies, particularly perovskites, face challenges related to long-term stability and environmental degradation.
- Commercial Availability: These technologies are still in the experimental phase or limited commercial production, which may impact their availability and cost-effectiveness.

4) Multi-Junction Solar Cells:

Advantages:

- Exceptional Efficiency: Multi-junction cells can achieve efficiencies greater than 40% under concentrated sunlight, due to their ability to capture a broader range of the solar spectrum.
- Performance in High Light Conditions: They are highly efficient under concentrated solar conditions, making them suitable for high-performance applications.

Limitations:

- Cost: The complexity of manufacturing and the use of rare materials result in high production costs, which may be prohibitive for commercial drone applications.

Weight and Integration: The structure of multi-junction cells can be complex and may add weight, potentially impacting drone performance.

3. Conclusion

In the design of solar panel drones, the choice of solar cells is pivotal. Silicon-based cells offer high efficiency and durability but are limited by weight. Thin-film cells provide flexibility and lower costs but suffer from lower efficiency and shorter lifespan. Emerging and specialized cells promise significant advancements in efficiency and flexibility but face challenges in stability and commercialization. Multi-junction cells deliver unmatched efficiency but at a high cost and weight. Each type of solar cell has its trade-offs, and the optimal choice will depend on the specific requirements of the drone's mission, including payload capacity, flight duration, and environmental conditions.

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