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Innovative Power Strategies for CubeSats: Enhancing Solar Energy Capture and Efficient Storage Solutions

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Abstract: CubeSats, a revolutionary class of small satellites, have significantly democratized access to space by offering compact, cost-effective, and highly versatile platforms for scientific, commercial, and educational applications. These miniaturized spacecrafts have become indispensable tools for conducting Earth observation, atmospheric studies, deep-space exploration, and technology demonstrations. However, the efficient management of power systems remains a critical challenge due to the constraints imposed by their small size, limited surface area for solar energy harvesting, and the harsh conditions of space. This paper explores innovative approaches to optimizing the energy systems of CubeSats, focusing on advancements in solar energy harvesting, energy storage technologies, and power management strategies. It highlights the potential of high- efficiency photovoltaic materials, such as multi-junction and perovskite solar cells, to enhance energy capture by utilizing broader portions of the solar spectrum. The study also examines energy storage technologies, including lithium-ion, lithium-polymer, and emerging solid-state batteries, comparing their performance, reliability, and applicability in space missions. Furthermore, hybrid energy storage systems, which combine different storage technologies like batteries and supercapacitors, are analyzed for their ability to dynamically balance energy supply and demand, ensuring stability and efficiency under variable conditions. The research delves into advanced optimization techniques, such as Maximum Power Point Tracking (MPPT) algorithms, which adaptively maximize energy extraction from solar panels, and thermal management strategies that mitigate efficiency losses due to overheating. Load scheduling, depth-of-discharge control, and real-time diagnostics are discussed as critical strategies to extend battery lifespan and ensure continuous operation. Mathematical models and experimental data are integrated to validate these techniques and provide actionable insights for the design and operation of CubeSat energy systems. By addressing the unique challenges of CubeSat power management, this study contributes to the development of robust, sustainable, and high-performance energy solutions. These advancements not only enhance CubeSat mission capabilities and longevity but also pave the way for more ambitious applications, including interplanetary exploration and multi- satellite constellations. The findings of this research are intended to benefit academia, space agencies, and industries, fostering innovation in small satellite technology and expanding the possibilities for cost-effective and impactful space exploration.

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1. Introduction

CubeSats are a class of small satellites with form factor of 10 cm (3.9 in) cubes. CubeSats have a mass of no more than 2 kg (4.4 lb) per unit, and often use commercial off-the-shelf (COTS) components for their electronics and structure. CubeSats are deployed into orbit from the International Space Station or launched as secondary payloads on a launch vehicle. As of December 2023, more than 2,300 CubeSats have been launched. Professors Jordi Puig-Suari of California Polytechnic State University and Bob Twiggs of Stanford University proposed the CubeSat reference design in 1999 with the aim of enabling graduate students to design, build, test and operate in space a spacecraft with capabilities like that of the first spacecraft, Sputnik **[16][17]**. The CubeSat, as initially proposed, did not set out to become a standard; rather, it became a standard over time by a process of emergence. The first CubeSats launched in June 2003 on a Russian Eurockot, and approximately 75 CubeSats had entered orbit by 2012.

The need for such a small-factor satellite became apparent in 1998 as a result of work done at Stanford University's Space System Development Laboratory. At SSDL, students had been working on the OPAL (Orbiting Picosatellite Automatic Launcher) microsatellite since 1995 **[33]**. OPAL's mission to deploy daughter-ship "picosatellites" had resulted in the development of a launcher system that was "hopelessly complicated" and could only be made to work "most of the time". With the project's delays mounting, Twiggs sought DARPA funding that resulted in the redesign of the launching mechanism into a simple pusher-plate concept with the satellites held in place by a spring-loaded door **[17]**.

Desiring to shorten the development cycle experienced on OPAL and inspired by the picosatellites OPAL carried, Twiggs set out to find "how much could you reduce the size and still have a practical satellite". The picosatellites on OPAL were 10.1 cm × 7.6 cm × 2.5 cm (4 in × 3 in × 1 in), a size that was not conducive to covering all sides of the spacecraft with solar cells. Inspired by a 4 in (10 cm) cubic plastic box used to display Beanie Babies in stores, Twiggs first settled on the larger ten-centimetre cube as a guideline for the new CubeSat concept. A model of a launcher was developed for the new satellite using the same pusher-plate concept that had been used in the modified OPAL launcher. Twiggs presented the idea to Puig-Suari in the summer of 1999 and then at the Japan–U.S. Science, Technology and Space Applications Program (JUSTSAP) conference in November 1999 **[17][33]**.

The term "CubeSat" was coined to denote nanosatellites that adhere to the standards described in the CubeSat design specification. Cal Poly published the standard in an effort led by aerospace engineering professor Jordi Puig-Suari. Bob Twiggs, of the Department of Aeronautics & Astronautics at Stanford University, and currently a member of the space science faculty at Morehead State University in Kentucky, has contributed to the CubeSat community. His efforts have focused on CubeSats from educational institutions. The specification does not apply to other cube-like nanosatellites such as the NASA "MEPSI" nanosatellite, which is slightly larger than a CubeSat. GeneSat-1 was NASA's first fully automated, self-contained biological spaceflight experiment on a satellite of its size. It was also the first U.S.-launched CubeSat **[4]**. This work, led by John Hines at NASA Ames Research, became the catalyst for the entire NASA CubeSat program **[20][25]**. In 2017, this standardization effort led to the publication of ISO 17770:2017 by the International Organization for Standardization. This standard defines specifications for CubeSats including their physical, mechanical, electrical, and operational requirements. It also provides a specification for the interface between the CubeSat and its launch vehicle, which lists the capabilities required to survive the environmental conditions during and after launch and describes the standard deployment interface used to release the satellites. The development of standards shared by many spacecrafts contributes to a significant reduction in the development time and cost of CubeSat missions.

These miniature satellites based on their standardized cube-shaped units, have revolutionized space research and technology development due to their compact size, affordability, and versatility. These small satellites offer a cost-effective alternative to traditional spacecraft, allowing universities, startups, and developing countries to participate in space exploration. Their low cost and ease of production make them ideal for conducting high-risk experiments and testing innovative technologies, fostering rapid advancements in space science and engineering.

Another key benefit of CubeSats is their rapid development cycle. Unlike traditional satellites that may take years to design and deploy, CubeSats can be built and launched within months. This agility accelerates innovation, enabling researchers to test ideas and iterate quickly. Furthermore, CubeSats play a crucial role in education by providing hands- on experience in satellite design, construction, and operations for students and early-career researchers, thereby enhancing STEM education and workforce development.

These miniaturized satellites have proven their value in diverse scientific applications, including Earth observation, atmospheric studies, and deep-space exploration. They provide valuable data for monitoring climate change, tracking natural disasters, and studying celestial phenomena, contributing to breakthroughs in both Earth and space sciences. Additionally, CubeSats are often used as platforms for technology demonstration, testing novel sensors, propulsion systems, and communication devices on a smaller, more manageable scale.

The affordability and modularity of CubeSats make space more accessible, democratizing opportunities for smaller organizations and fostering global collaboration in space exploration. Their standardized design ensures compatibility with various launch systems, and they are often launched as secondary payloads, further reducing costs. CubeSats also complement larger missions, performing critical tasks such as data relay, risk assessment, and surveying regions of interest, while their short operational lifespan minimizes space debris.

In summary, CubeSats have transformed the landscape of space research by lowering barriers to entry and enabling innovative, cost-effective missions. Their impact spans scientific discovery, educational growth, and technological advancement, making them an indispensable tool for the future of space exploration

2. Literature Review

CubeSats, a revolutionary class of small satellites, have gained significant attention since their inception in 1999 by Jordi Puig-Suari and Bob Twiggs. The initial concept was driven by the need for a cost-effective and scalable satellite design that could be utilized for educational purposes and scientific research. CubeSats follow a standardized design specification, as outlined by the CubeSat Design Specification, which was further formalized by ISO 17770:2017 to ensure uniformity in physical, mechanical, and operational requirements **[16][17]**.

Early CubeSat missions, such as the OPAL microsatellite and subsequent CubeSat deployments, highlighted the transformative potential of these systems. Their ability to integrate commercial off-the-shelf (COTS) components drastically reduced costs and development cycles compared to traditional satellites. Studies have shown CubeSats to be instrumental in advancing space science by democratizing access to space, allowing universities, startups, and smaller nations to participate in research activities **[3]**.

Power generation and storage are critical components in CubeSat design. Literature highlights the evolution from simple fixed solar panels to advanced technologies like multi-junction solar cells and emerging perovskite cells, which offer enhanced efficiency. Energy storage has similarly advanced, with lithium-ion batteries dominating due to their energy density, while solid-state batteries are emerging as safer, more durable alternatives. Optimization techniques like Maximum Power Point Tracking (MPPT) and load scheduling have further enhanced CubeSat energy systems, allowing for efficient power utilization even under challenging conditions. Research into electrodynamic tethers and hybrid energy systems is pushing the boundaries of propulsion and power generation in space. However, challenges such as thermal management and reliability in extreme environments remain areas of active exploration **[5]**.

The literature underscores CubeSats' broad applicability in Earth observation, atmospheric studies, and deep-space exploration. Studies emphasize their role in technology demonstration, enabling the rapid testing of novel propulsion systems, sensors, and communication devices. These contributions establish CubeSats as a cornerstone for future innovations in space exploration.

3. Methodology Proposed

3.1 Limited Efficiency of Solar Panels

Problem: Conventional solar panels, such as monocrystalline and polycrystalline types, convert only a portion (typically 13–22%) of the sunlight into usable energy. This efficiency is insufficient for CubeSats, where the available surface area for mounting solar panels is extremely limited due to their compact form factor.

Impact: The restricted power generation capability results in energy shortages, especially for missions requiring high power output, such as those involving advanced sensors, communication systems, or propulsion technologies.

Paper's Contribution:

The study investigates high-efficiency photovoltaic materials like multi-junction solar cells, which achieve efficiencies exceeding 30% by utilizing multiple layers that capture a broader spectrum of sunlight. It also highlights perovskite solar cells, a rapidly emerging technology that offers efficiencies up to 25%, along with low production costs and tunable properties for specific CubeSat applications.

3.2 Suboptimal Energy Harvesting:

Problem: Solar panels on CubeSats are often fixed or body-mounted, leading to inconsistent energy capture as the satellite's orientation relative to the Sun changes. Moreover, standard solar energy systems lack dynamic optimization techniques to adapt to varying light conditions.

Impact: Energy is lost during orbital transitions or when solar panels are not optimally aligned with the Sun, reducing the overall power budget.

Paper's Contribution:

The research focuses on Maximum Power Point Tracking (MPPT) algorithms, which dynamically adjust the operating conditions of solar panels to extract maximum power regardless of irradiance and temperature fluctuations **[30]**. Tilt and orientation control strategies are introduced to align solar panels with the Sun's trajectory, enhancing energy capture by up to 40%.

3.3 Thermal Management Challenges:

Problem: Solar panels and batteries generate heat during operation, and in the vacuum of space, this heat has no medium to dissipate. Excessive temperatures reduce the efficiency of solar cells and degrade battery components, leading to potential failures.

Impact: High operational temperatures cause thermal stress, reducing the lifespan and efficiency of critical power components. Inadequate thermal regulation can lead to mission-ending power system failures.

Paper's Contribution:

The study highlights passive cooling techniques, such as radiative cooling surfaces, heat sinks, and thermally conductive materials, to dissipate heat efficiently. Active cooling methods, like phase-change materials (PCMs), are explored, which absorb excess heat as they transition from solid to liquid, stabilizing the operating temperature of solar panels and batteries.

3.4 Limited Energy Storage Options:

Problem: Conventional energy storage technologies, such as nickel-cadmium (NiCd) or early lithium-ion batteries, offer limited energy density and may not meet the demanding power storage needs of CubeSat missions.

Impact: Inadequate energy storage compromises mission objectives, particularly during eclipse phases or high- power-demand periods, when solar energy generation is not possible.

Paper's Contribution:

Advanced storage solutions like solid-state batteries are explored for their higher energy density, safety, and longevity compared to traditional lithium-ion batteries. Hybrid energy storage systems (HESS), which combine batteries with supercapacitors, are proposed to balance energy supply and demand, ensuring stable power delivery and efficient use of stored energy **[5]**.

3.5 Short Operational Lifespan of Batteries:

Problem: The frequent charge-discharge cycles in space, coupled with radiation exposure and thermal stress, degrade the performance of traditional batteries over time.

Impact: Reduced battery life leads to shortened CubeSat missions, particularly for long-duration or deep-space explorations where battery replacement is not an option.

Paper's Contribution:

Techniques like depth-of-discharge (DoD) control are presented to minimize stress on batteries by restricting their usage within optimal limits (e.g., 20–80% charge capacity), significantly extending their cycle life. Real-time diagnostics and redundancy in battery systems ensure continuous operation even in the event of partial failures.

3.6 Energy Variability in Space:

Problem: Solar energy generation fluctuates due to orbital transitions, eclipses, and shadows cast by another spacecraft. Additionally, the harsh space environment introduces unpredictable variations in power availability.

Impact: Energy shortages during critical operations, such as communication or data collection, can result in mission failures or data loss.

Paper's Contribution:

Hybrid energy systems are emphasized to dynamically manage power fluctuations. Batteries store large amounts of energy for long-term use, while supercapacitors handle rapid energy bursts for peak demand.

The study also integrates real-time energy monitoring systems to predict and adapt to power supply variability effectively.

3.7 High Risk of Radiation Damage:

Problem: Solar panels and batteries are vulnerable to radiation in space, which can degrade their performance over time. Conventional materials, like standard silicon cells, have low resistance to radiation-induced efficiency losses.

Impact: Radiation exposure reduces the longevity and reliability of power systems, particularly for CubeSats operating in high-radiation environments like geostationary orbits.

Paper's Contribution:

The study examines radiation-resistant materials such as CIGS (Copper Indium Gallium Selenide) and multi-junction solar cells, which maintain efficiency even under prolonged radiation exposure. Improved shielding and design considerations are suggested to mitigate radiation damage.

3.8 Inefficiency During Low-Light or Eclipse Periods:

Problem: CubeSats face prolonged periods without sunlight during eclipse phases, limiting their ability to generate power. Conventional systems lack alternative energy sources to compensate for the absence of sunlight.

Impact: The reliance on stored energy during eclipse periods limits the CubeSat's operational capabilities, potentially leading to mission interruptions.

Paper's Contribution:

Alternative power solutions, such as radioisotope power systems (RPS), are explored for missions beyond Earth's orbit, where sunlight is scarce. These systems provide reliable energy by converting heat from radioactive decay into electricity. The integration of solar sails with energy-harvesting capabilities is proposed for interplanetary missions, where traditional solar panels are less effective.

4. Power Generation Techniques

CubeSats employ a variety of power generation techniques tailored to their compact design and operational requirements. The most common and reliable method is the use of solar panels, which harness sunlight to produce electricity. Solar panels can be mounted directly onto the CubeSat's surface (fixed solar panels) or designed to deploy after the satellite reaches orbit. Deployable panels provide a larger surface area for energy capture, making them suitable for missions with higher power demands. Body-mounted solar panels, on the other hand, are integrated across the satellite's exterior to ensure continuous power generation regardless of its orientation, though efficiency may vary depending on its position relative to the Sun [3].

Advanced solar technologies are also gaining prominence in CubeSat missions. Multi-junction solar cells, for instance, utilize multiple semiconductor layers to capture a broader spectrum of sunlight, achieving higher efficiencies compared to traditional silicon cells. Flexible solar arrays are another innovation, offering lightweight and adaptable options that maximize energy generation while minimizing the satellite's weight.

4.1 Solar panel types:

Monocrystalline Solar Cells:

- **Structure:** Made from a single, continuous crystal structure.
- **Efficiency:** Typically, the most efficient, with efficiencies around 15-22%.
- **Advantages:** High efficiency, long lifespan, and good performance in low-light conditions.
- **Applications:** Used in CubeSats requiring high power output and reliability.

Polycrystalline Solar Cells:

- **Structure:** Made from multiple silicon crystals.
- **Efficiency:** Slightly lower than monocrystalline cells, with efficiencies around 13-16%.
- **Advantages:** Lower cost compared to monocrystalline cells, good performance in moderate climates.
- **Applications:** Suitable for CubeSats with moderate power requirements and budget constraints.

Thin-Film Solar Cells:

- **Structure:** Made by depositing one or more thin layers of photovoltaic material on a substrate.
- **Efficiency:** Generally lower than crystalline silicon cells, with efficiencies around 7-13%.
- **Advantages:** Lightweight, flexible, and can be produced at lower costs.

- **Applications:** Ideal for CubeSats with size and weight constraints, and where flexibility is required.

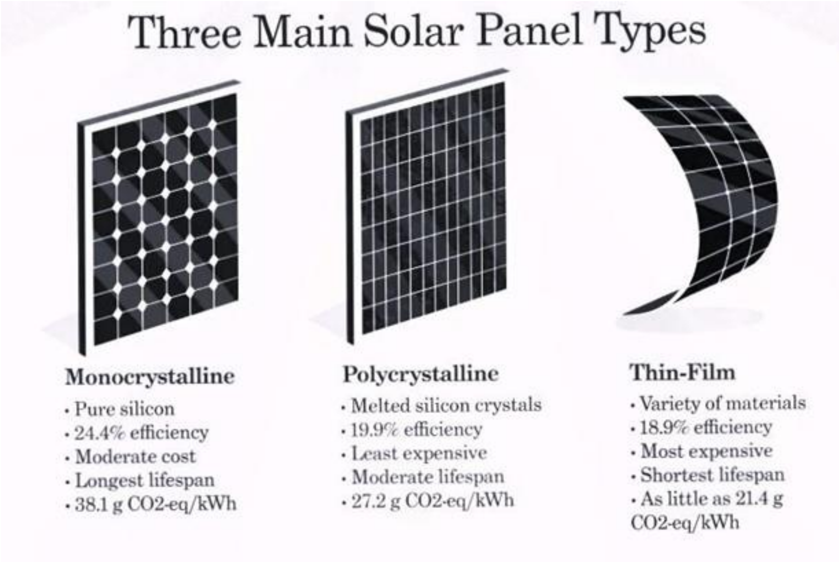


Figure-1 Three different types of Solar cells.

[Source: Treehugger]

Multi-Junction Solar Cells:

- **Structure:** Composed of multiple layers of different semiconductor materials.
- **Efficiency:** Very high efficiencies, up to 30% or more.
- **Advantages:** Can capture a broader spectrum of sunlight, leading to higher efficiency.
- **Applications:** Used in high-performance CubeSats requiring maximum power output.

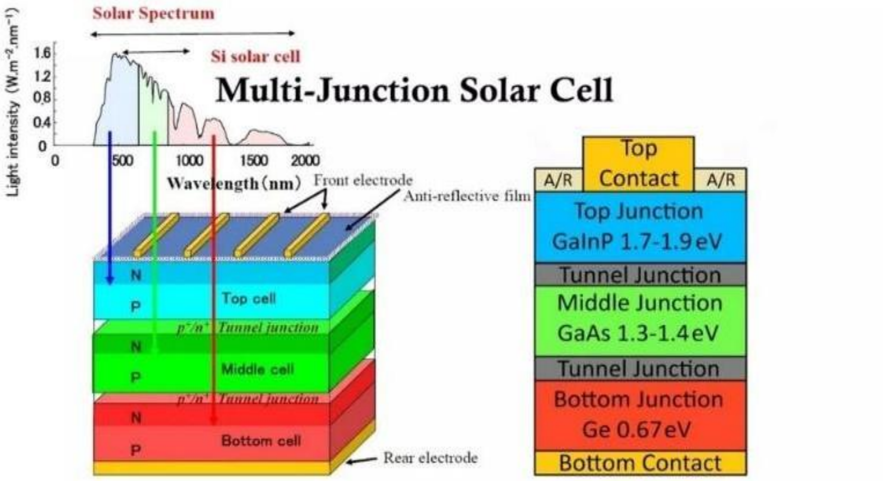


Figure-2 Multi-Junction Solar cells

[Source: Hacktronic]

Perovskite Solar Cells:

- **Structure:** Made from perovskite-structured materials.
- **Efficiency:** Rapidly improving, with efficiencies reaching around 20-25%.
- **Advantages:** Low production costs, potential for high efficiency, and tunable bandgap.

- **Applications:** Emerging technology with potential for future CubeSat missions

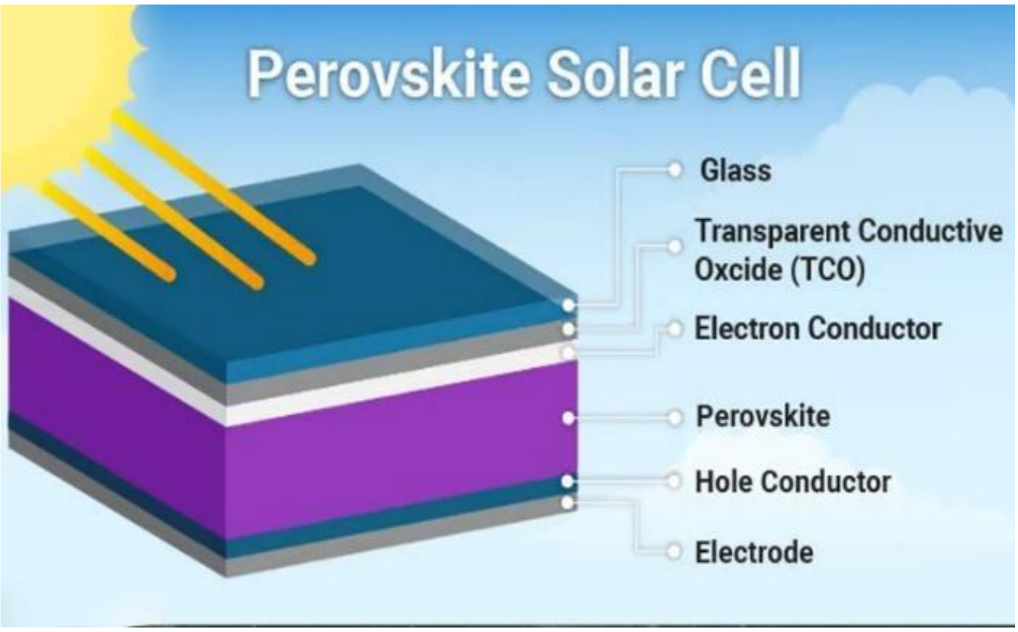


Figure-3 Different Layers of Perovskite Solar Cells

[Source: Soleosenergy]

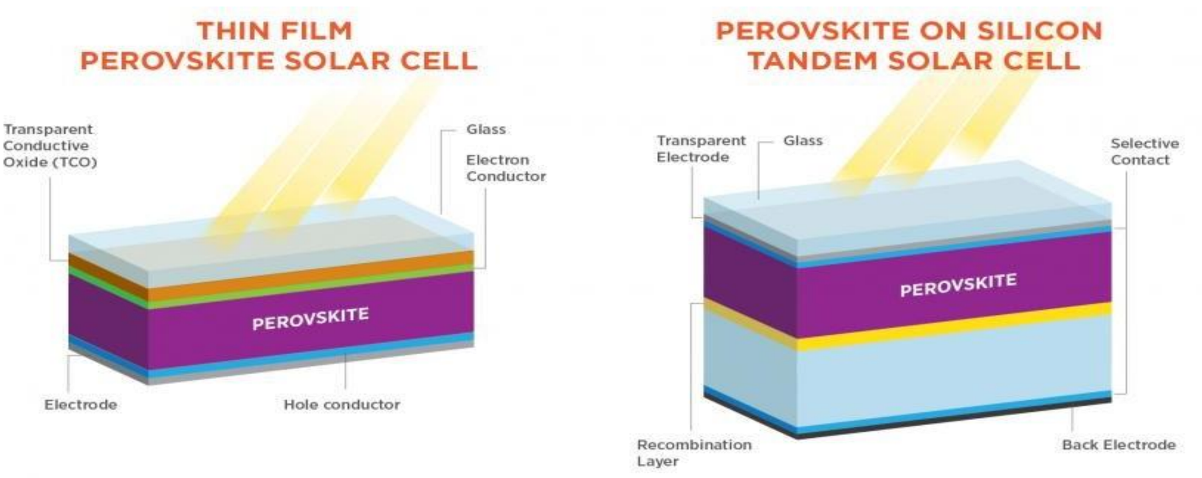


Figure-4 Two types of Perovskite solar cells.

[Source: Sunbasedata]

CIGS Solar Cells (Copper Indium Gallium Selenide):

- **Structure:** Made from a thin film of CIGS material.
- **Efficiency:** Around 10-12%.
- **Advantages:** Good performance in low-light conditions, flexible, and lightweight.

- **Applications:** Suitable for CubeSats with specific environmental requirements.

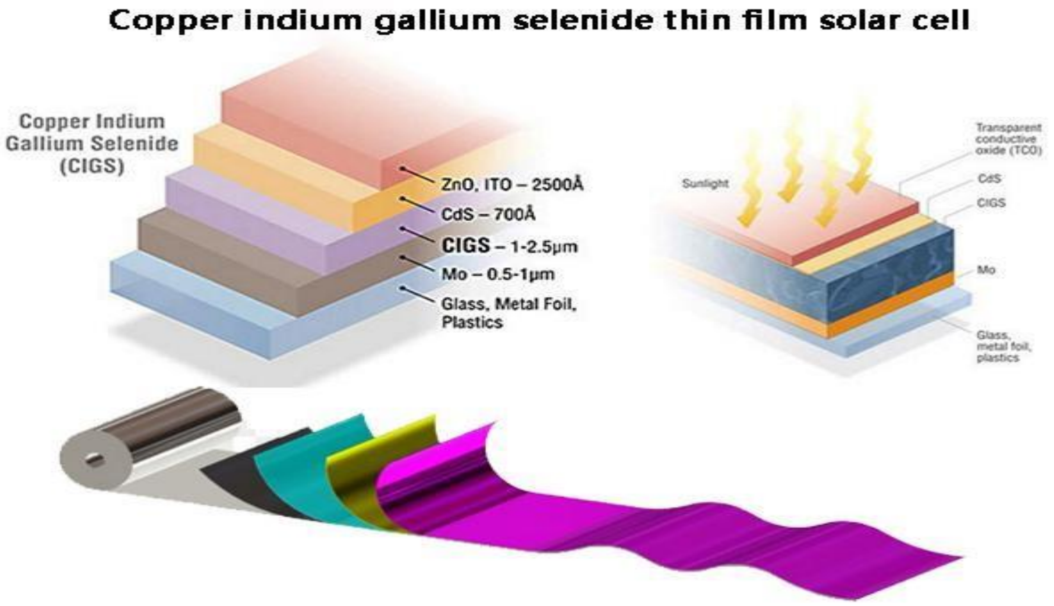


Figure-5 Composition of CIGS Solar Cells

[Source: Openpr]

4.2 Efficiency and Performance comparison of the mentioned solar cell types:

Efficiency Comparison: This bar chart shows that Multijunction solar cells have the highest efficiency (40%), followed by Perovskite (25%) and Monocrystalline (22%). Thin-film cells show the lowest efficiency at 12% [31].

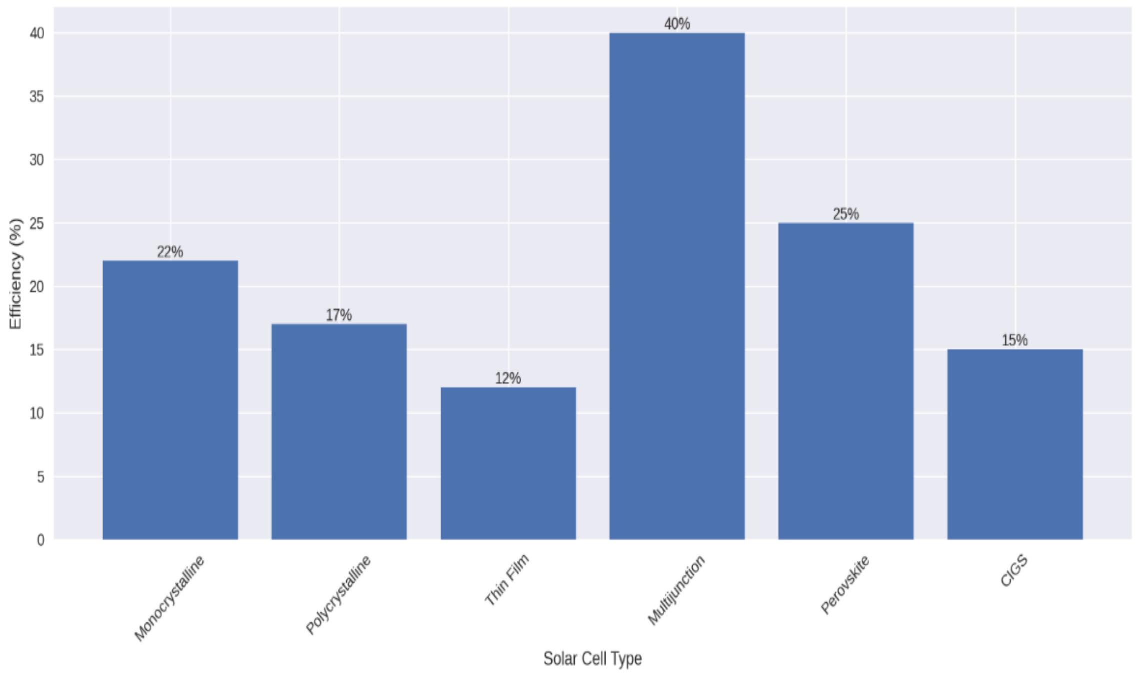
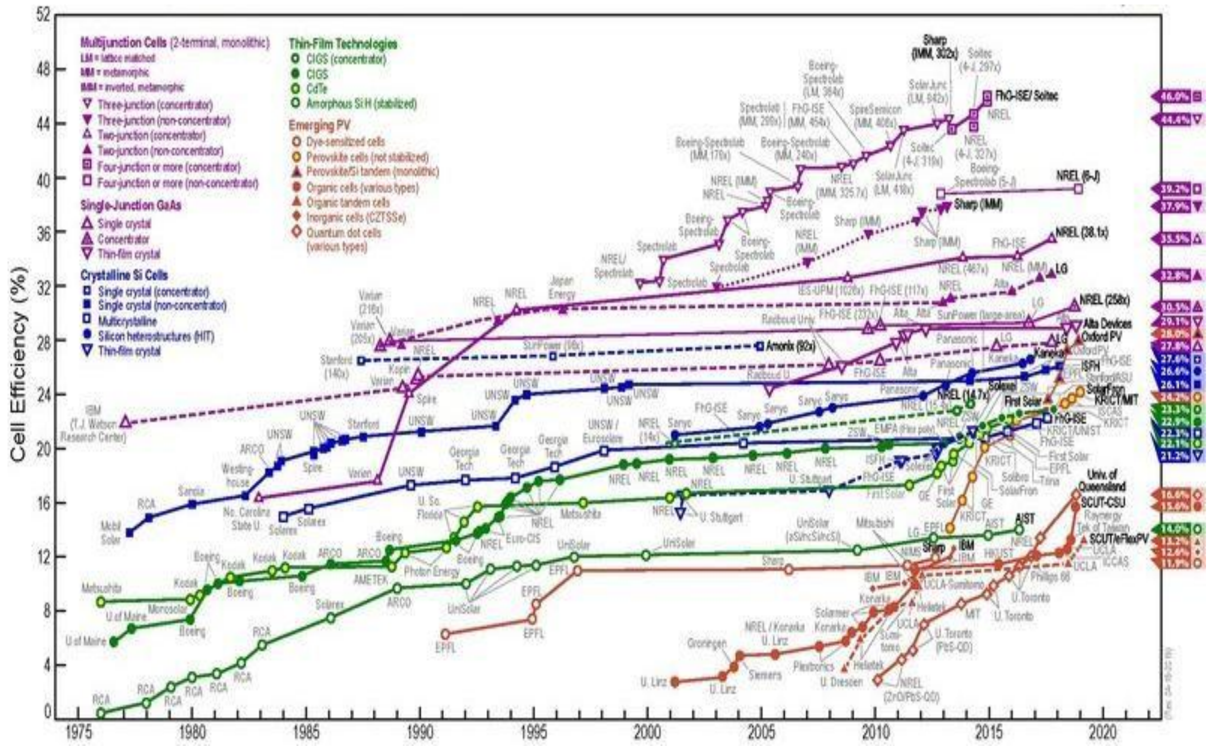


Figure-6 (A) Solar Cell Efficiency Comparison



(B)

[Source: https://en.wikipedia.org/wiki/Solar_cell_research]

Figure-6 A &B Efficiency of different types of solar cells

Radiation Resistance vs Thermal Stability: This scatter plot shows how different solar cells perform in the space environment. Multijunction cells excel in both aspects, while Perovskite cells show lower resistance to both conditions. CIGS and Thin-film cells show balanced performance.

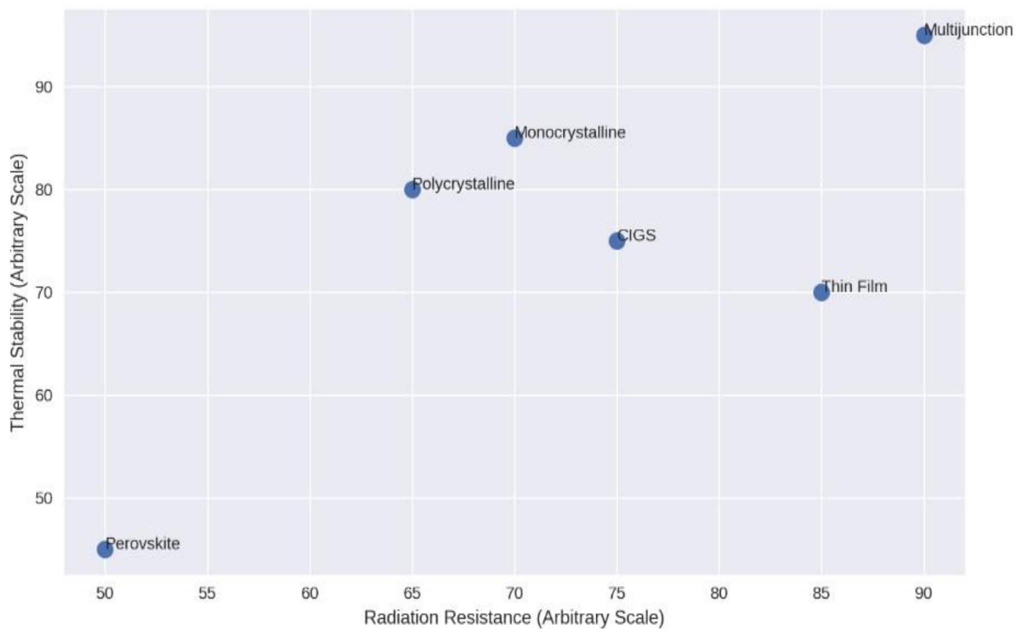


Figure-7 Radiation Resistance vs Thermal Stability

Temperature Coefficient: This shows how much the cell's performance decreases per degree Celsius increase. Perovskite cells have the worst temperature coefficient (-0.8%/°C), while Multijunction cells perform best (-0.2%/°C).

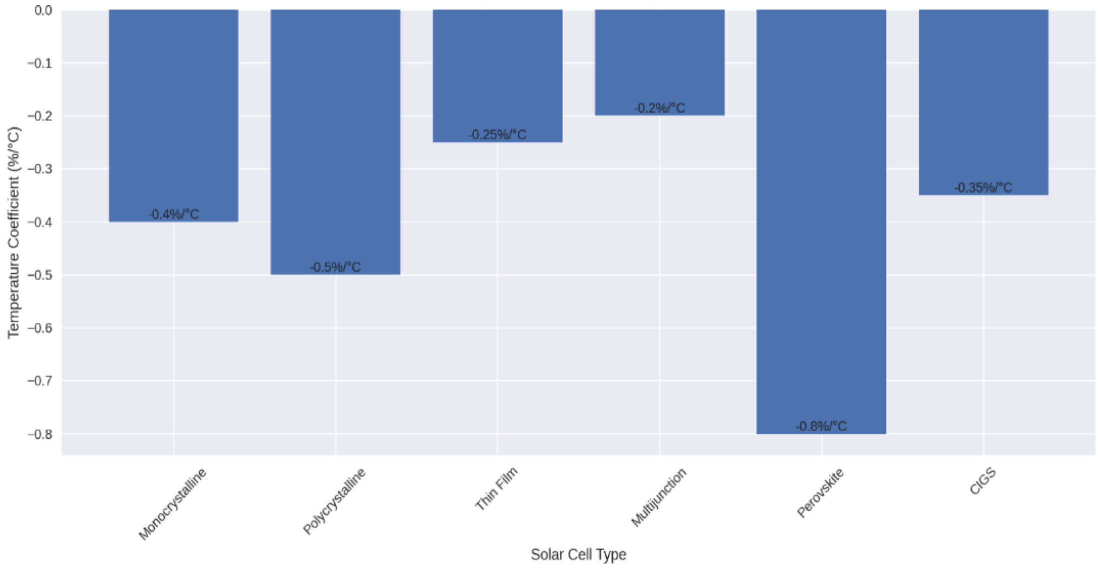


Figure-8 Temperature Coefficient Comparison

Voltage Output: Multijunction cells stand out with the highest voltage output (2.8V), while thin-film cells have the lowest (0.55V). This is particularly important for CubeSat power systems design.

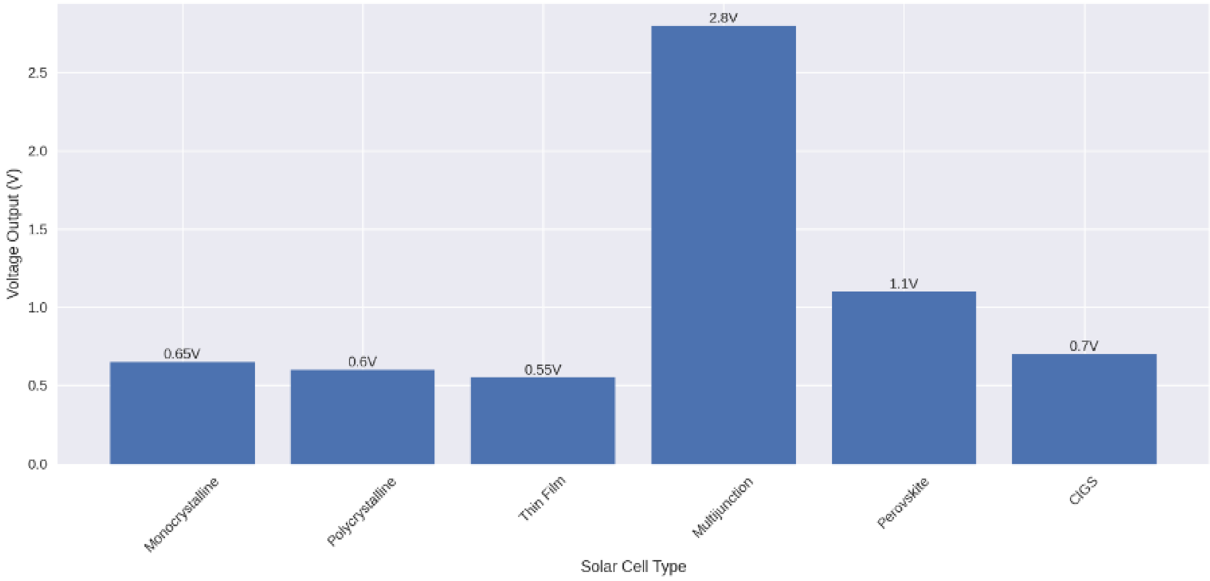


Figure-9 Voltage Output Comparison

Current Output: Multijunction cells again stands out with the highest current output (7.5A), while thin-film cells have the lowest current output (4.0A).

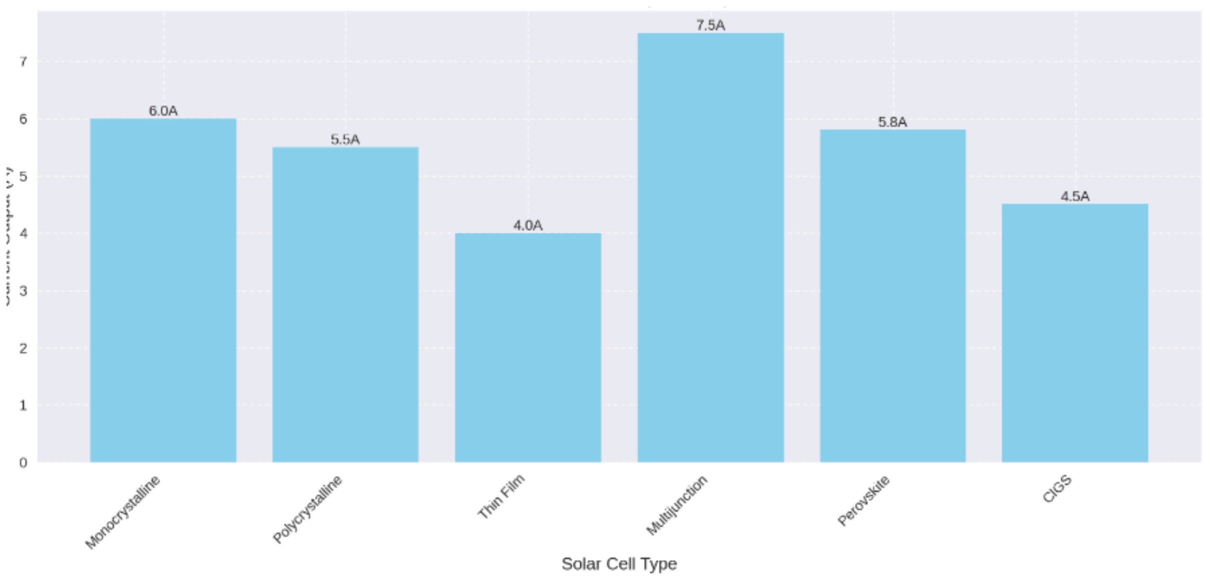


Figure-10 Solar Cell Current Output Comparison

Spider/Radar Chart: This normalized comparison shows the overall performance across all metrics. Multijunction cells (shown by their larger area) demonstrate superior overall performance, while each technology shows its unique strengths and weaknesses.

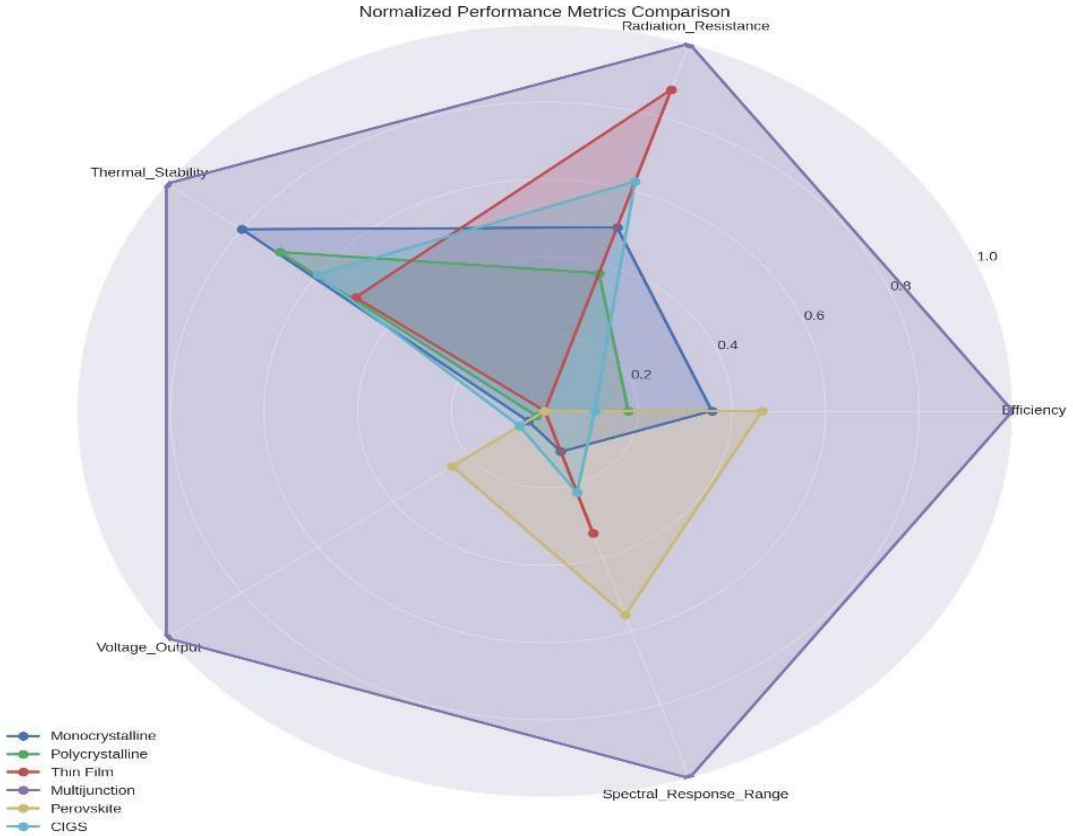


Figure-11 Normalized Performance Metrics Comparison

Key Takeaways:

- Multijunction cells shows the best overall performance but are typically more expensive.
- Perovskite cells show promising efficiency but need improvement in stability.
- Thin-film cells, while less efficient, show good radiation resistance.
- CIGS cells offer a balanced performance across most metrics.
- Mono and Polycrystalline cells provide reliable performance with moderate efficiency.

4.3 Alternative Power methods:

Electrodynamic tethers:

In addition to solar energy, CubeSats explore alternative energy harvesting methods to complement their power systems. Electrodynamic tethers generate electricity by interacting with Earth’s magnetic field, while thermoelectric materials convert temperature gradients between sunlight and shaded areas into power. Although these methods are less common, they hold potential for specific applications, such as deorbiting or enhancing energy generation in challenging environments [2].

Electrodynamic tethers (EDTs) are innovative technology used in CubeSats for propulsion and power generation without the need for traditional fuel sources. Here's an overview of how they work and their applications:

How Electrodynamic Tethers Work?

Electrodynamic tethers (EDTs) generate propulsion by conducting an electric current along a long wire (the tether) that connects two spacecraft end-masses. As the CubeSat moves along its orbital path, the Earth's magnetic field induces a Lorentz force between the magnetic field and the electrons in the tether, resulting in thrust. This method requires no chemical or traditional fuel source, making it a sustainable option for long-duration missions [26].

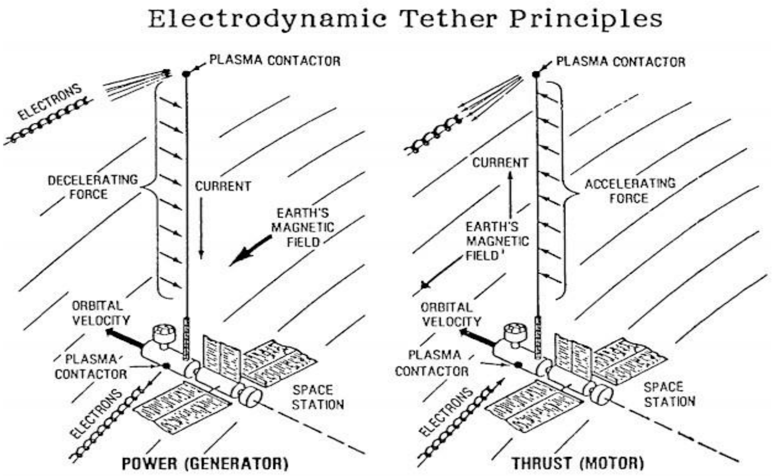


Figure-12: Electrodynamic tether principles.

[Source:Toughsf]

Applications in CubeSats: EDTs are used for various orbital maneuvers in CubeSats, including adjusting the satellite's orbit, changing the orientation of the orbit, and active maneuvering without expending traditional fuel. These capabilities are particularly valuable for enhancing the mission flexibility and lifespan of CubeSats.

Notable Experiments and Missions: One notable experiment involving EDTs is the Tether Electrodynamics Propulsion CubeSat Experiment (TEPCE) developed by the U.S. Naval Research Laboratory. TEPCE, a 3U CubeSat, demonstrated electrodynamic propulsion using a 1 km long conducting tether to generate thrust. The deployment mechanism for TEPCE used a spring deployment system called a "stacer" to push the two CubeSat end masses apart, initiating the tether's deployment.

Advantages: EDTs offer several advantages, including sustainability, cost-effectiveness, and the potential for extended mission life. Since they do not require traditional fuel, EDTs provide a sustainable propulsion method that reduces the need for carrying large amounts of fuel, thereby lowering mission costs. Additionally, EDTs enable longer missions by providing continuous propulsion without depleting onboard fuel resources [8].

Challenges: Despite their benefits, EDTs face challenges such as ensuring reliable deployment of the tether in space, managing the electrical current efficiently, and minimizing interference from the Earth's magnetic field. These challenges must be addressed to fully realize the potential of EDTs in CubeSat missions.

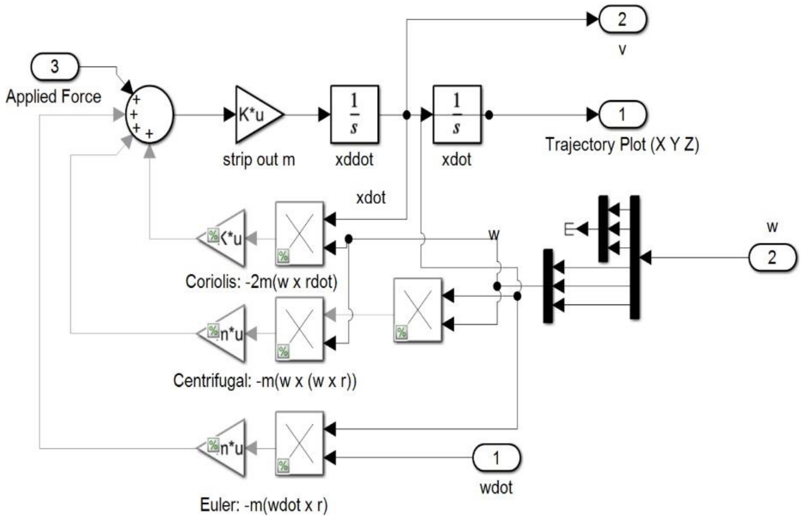


Figure-13 Schematic representation of Electrodynamic tether.

Energy storage is an essential component of CubeSat power systems. Lithium-ion batteries are the most widely used due to their high energy density and rechargeability, enabling the storage of solar energy for use during eclipse periods or when demand peaks. Supercapacitors, which allow rapid charging and discharging, are sometimes used for short-term power bursts, although they are less common as primary storage solutions.

Radioisotope power system:

For missions beyond Earth's orbit, where sunlight is scarce, RADIOISOTOPE POWER SYSTEMS (RPS) can be employed. These systems generate electricity by converting heat from radioactive decay, providing a reliable power source for deep-space CubeSats. Although rarely used due to size and cost constraints, they are a viable option for long-duration missions. RPS utilizes the heat generated from the natural decay of radioactive materials to produce electricity. This heat is converted into electrical power using thermoelectric generators (TEGs) or other conversion methods.

Key Components:

- **Radioisotope Fuel:** Typically, isotopes like Plutonium-238 are used due to their long half-lives and high heat output.
- **Thermoelectric Generators (TEGs):** Convert heat from the radioisotope into electricity using the Seebeck effect.
- **Heat Source:** The radioisotope fuel acts as the heat source.
- **Heat Sink:** A component that dissipates excess heat to maintain optimal operating temperatures.

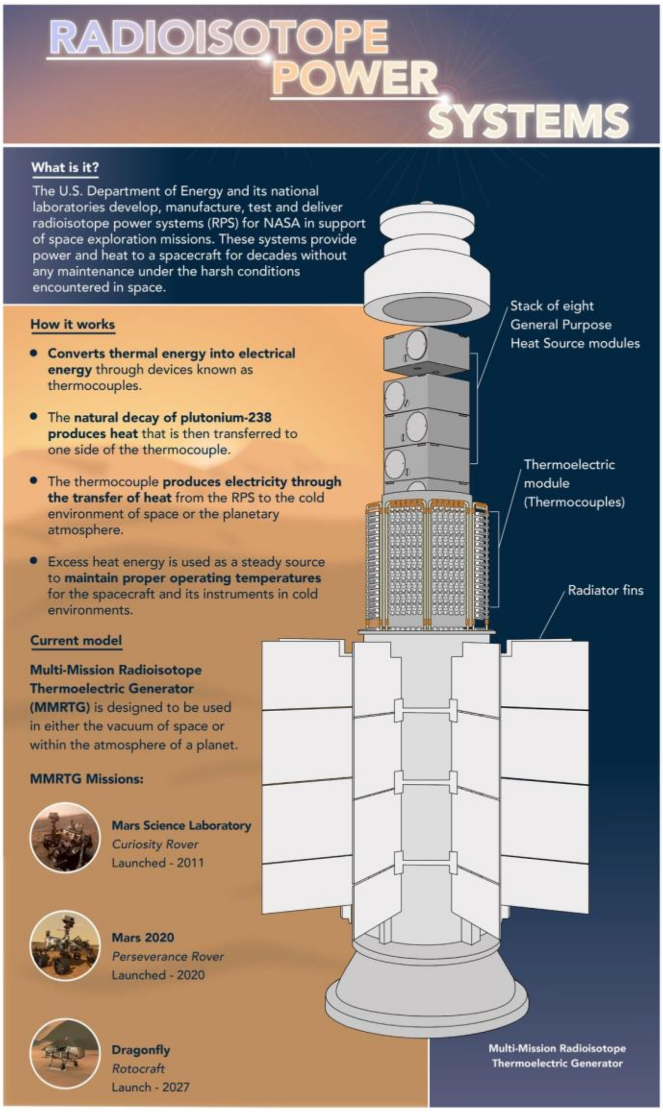


Figure-14 Multi-Mission Radioscope Thermoelectric Generator (MMRTG)

[Source: Energy.gov]

Advantages

- **Longevity:** RPS can provide power for many years, making them ideal for deep space missions.
- **Reliability:** They are less susceptible to environmental conditions compared to solar panels.

- **Continuous Power:** Unlike solar power, RPS can provide continuous power regardless of the spacecraft's orientation or distance from the sun.

Applications in CubeSats

- **Deep Space Missions:** CubeSats equipped with RPS can explore regions where solar power is insufficient **[32]**.
- **High-Reliability Missions:** Missions requiring consistent power supply without reliance on solar energy.
- **Extended Mission Durations:** CubeSats with RPS can have extended operational lifetimes, enabling long-term scientific research.

Challenges

- **Safety:** Handling and launching radioactive materials require stringent safety measures.
- **Cost:** Developing and integrating RPS can be expensive compared to conventional power systems.
- **Regulations:** Compliance with international regulations for the use of radioactive materials in space missions.

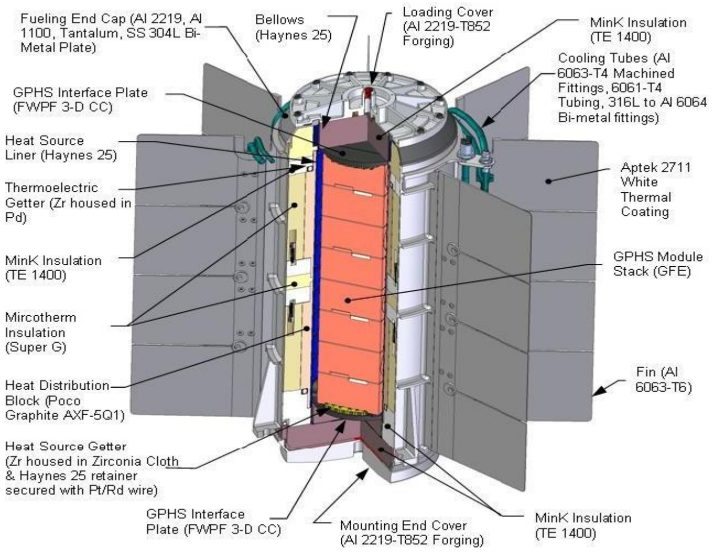


Figure-15 MMRTG Schematic.

[Source: ResearchGate]

Emerging technologies are also being explored to expand the power capabilities of CubeSats. Wireless power transfer, involving energy beaming from ground stations or other spacecraft, has the potential to support long-duration missions. Solar sails, primarily used for propulsion, can integrate solar cells to double as power generators, making them suitable for interplanetary CubeSats.

Ultimately, the choice of power generation technique depends on mission-specific factors such as duration, orbit, power requirements, and cost. By leveraging a combination of these methods, CubeSats can achieve reliable performance and extend their capabilities for a wide range of applications, from Earth observation to deep-space exploration.

5. Optimizing Techniques

5.1 MPPT

Maximum Power Point Tracking (MPPT) is an algorithm used in solar photovoltaic (PV) systems to maximize the power extraction under all conditions. Solar panels have a non-linear power-voltage (P-V) characteristic curve,

and the goal of MPPT is to find the operating point where the solar panel delivers its maximum power, called the Maximum Power Point (MPP).

Key Concepts of MPPT:

1. Solar Panel Characteristics:

- The power output of a solar panel depends on its current (I) and voltage (V).
- The power is calculated as $P = V \cdot I$
- The current-voltage (I-V) and power-voltage (P-V) curves vary with irradiance and temperature.

2. Maximum Power Point (MPP):

- At the MPP, the derivative of power with respect to voltage is zero ($\frac{dP}{dV} = 0$)
- Below the MPP, power increases with voltage, and above the MPP, power decreases with voltage.

3. Load Matching:

- The impedance seen by the panel must be matched to the internal impedance of the solar panel at the MPP to maximize power transfer.

Mathematical Derivation of MPPT:

Power-Voltage Relationship:

From Ohm's law, the current is given by the Shockley diode equation:

$$I = I_{\text{ph}} - I_0 \left(e^{\frac{q(V+IR_S)}{nkT}} - 1 \right) - \frac{V+IR_S}{R_{\text{sh}}} \quad \textbf{(1)}$$

Where,

- I_{ph} : Photogenerated current (depends on irradiance).
- I_0: Reverse saturation current.
- q: Charge of an electron (1.6×10^{-19} C).
- V: Voltage across the panel.
- R_s: Series resistance.
- R_{sh} : Shunt resistance.
- n: Ideality factor.
- k: Boltzmann constant (1.38×10^{-23} J/K).
- T: Temperature in kelvins.

Power Maximization:

Power is:

$$P = V \cdot I \quad \textbf{(2)}$$

$$\frac{dy}{dx} = \frac{d(VI)}{dV} = I + V\frac{dI}{dV} \quad (3)$$

Setting $\frac{dP}{dV} = 0$ at the MPP (Maximum Power Point):

$$I + V\frac{dI}{dV} = 0 \quad (4)$$

Rearranging:

$$\frac{dI}{dV} = -\frac{I}{V} \quad (5)$$

Impedance matching:

For maximum power transfer, the load impedance R_{load} must equal the source impedance R_{source}.

$$R_{load} = R_{source} = \frac{V_{mpp}}{I_{mpp}} \quad (5)$$

MPPT Algorithms:

1. Peturb and Observe (P&O)

- Periodically perturb V and observe changes in P.
- If ΔP>0, continue in the same direction; otherwise, reverse.

Example:

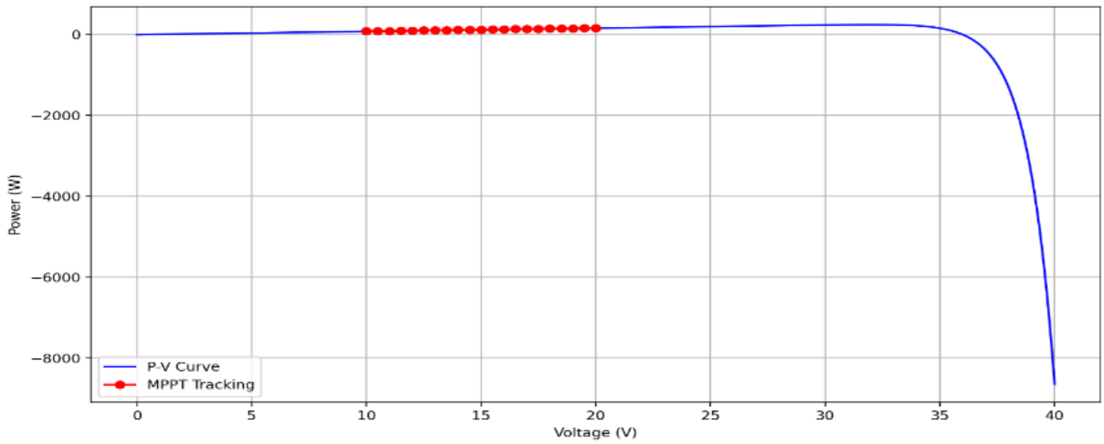


Figure-16 P&O Algorithm Simulation

The graph shows how the P&O algorithm tracks the maximum power point by making small voltage adjustments and observing the resulting power changes. The blue line represents the panel's P-V curve, while the red dots show the algorithm's tracking path.

2. Incremental Conductance (IC):

- Based on the condition $\frac{dP}{dV} = 0$ at MPP:

$$\frac{dI}{dV} = \frac{I}{V}$$

- Left of MPP:

$$\frac{dI}{dV} > -\frac{I}{V}$$

- Right of MPP:

$$\frac{dI}{dV} < -\frac{I}{V}$$

3. Constant Voltage (CV)

Assumes VMPP is a constant fraction of the open-circuit voltage (VOC).

Example:

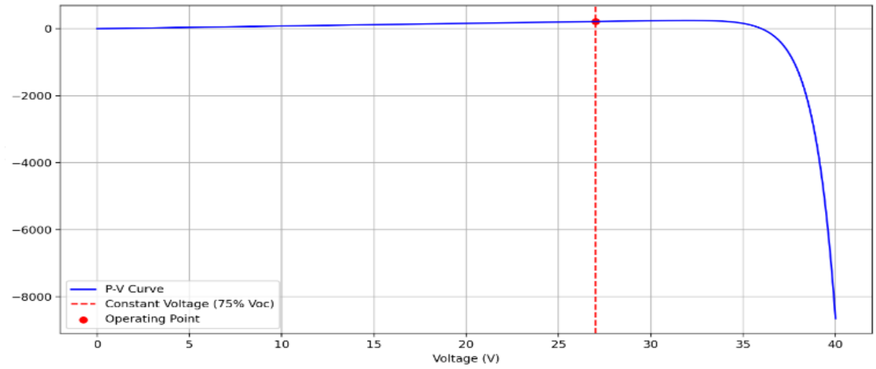


Figure-17 Constant Voltage MPPT Algorithm Simulation

4. Fuzzy Logic and Neural Networks:

Example:

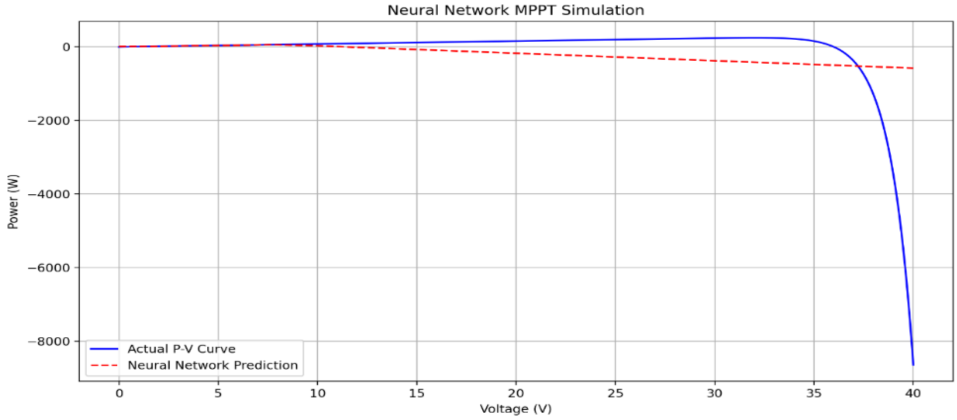


Figure-18 Neural Network MPPT Simulation

The graph shows both the actual P-V curve (blue) and the neural network's prediction (red dashed). The neural network has learned to accurately model the P-V characteristics, which can be used for MPPT control.

Efficiency Considerations:

MPPT improves system efficiency significantly, especially under:

- Variable irradiance (clouds, shading).
- Temperature changes.
- Non-optimal orientation or aging panels.

Example Calculation:

Given:

- Open-circuit voltage (V_{OC}): 40 V.
- Short-circuit current (I_{SC}): 8 A.
- $V_{MPP} = 0.76$; $V_{OC} = 30.4$ V
- $I_{MPP} = 0.9$; $I_{SC} = 7.2$ A

Power at MPP:

$$P_{MPP=} V_{MPP} \cdot I_{MPP} = 30.4 \cdot 7.2 = 218.88W$$

Using an MPPT controller ensures the load impedance matches the panel's impedance to achieve this power.

Applications of MPPT:

- Solar inverters.
- Battery charging systems.
- Grid-tied and off-grid solar systems.

5.2 Tilt and Orientation Control

Tilt and orientation control is a critical optimization technique in solar energy systems, designed to maximize the amount of sunlight captured by solar panels. By aligning the panels with the sun's trajectory, this method ensures optimal exposure, thus improving energy conversion efficiency **[22]**. Here's how it works:

1. Maximizing Incident Solar Irradiance

Tilt Adjustment:

- Adjusting the tilt angle ensures that sunlight strikes the panel surface as perpendicularly as possible.
- For fixed systems, the tilt is set to an optimal angle based on the geographic latitude and seasonal variations.
- Dynamic systems continuously adjust the tilt to match the sun's elevation angle throughout the day or year.

Orientation Adjustment:

- Aligning the azimuth angle of the panel (its compass direction) to face the sun improves the panel's exposure to direct sunlight.
- Panels in the northern hemisphere typically face true south, while those in the southern hemisphere face true north.

2. Enhancing Energy Conversion Efficiency

- By minimizing the angle of incidence (θ), more solar irradiance reaches the panel.

- Reduced angle of incidence leads to less reflection and more energy absorption by the photovoltaic material.

3. Dynamic Optimization with Trackers

Single-Axis Trackers:

Adjust the panel orientation (east-west) throughout the day to follow the sun's azimuthal movement.

Dual-Axis Trackers:

Simultaneously adjust tilt and orientation to maintain perpendicular alignment with the sun's rays, maximizing energy capture in real-time.

4. Mathematical Basis for Optimization

Maximizing Solar Power (PPP):

- The power output of a solar panel is proportional to the incident irradiance (I):

$$P = \eta \cdot A \cdot I \cdot cos\Theta \quad \textbf{(8)}$$

Where:

η: Efficiency of the solar panel.

A: Area of the solar panel.

I: Solar irradiance.

cos θ: Factor representing alignment between the sunlight and panel surface.

- Optimizing tilt and orientation minimizes θ, maximizing cos θ, and hence P.

5. Seasonal and Daily Optimization

Fixed panels may use seasonally adjusted angles:

- Winter: Steeper tilt to capture lower solar angles.
- Summer: Shallower tilt to capture higher solar angles.

Dynamic systems adjust both tilt and orientation to capture maximum irradiance throughout the day and across seasons.

6. Energy Harvesting Benefits

Increases daily and annual energy yields significantly, often by 20-30% for single-axis trackers and up to 40% for dual-axis systems **[6]**.

Enhances system efficiency and reduces the Levelized Cost of Energy (LCOE) for solar installations.

Use in Practice:

Tilt and orientation control is implemented in:

- Residential Systems: Optimized for a fixed tilt based on location.
- Utility-Scale Solar Farms: Utilize trackers for large-scale, dynamic optimization.
- Hybrid Systems: Combine tilt adjustments with MPPT for maximum energy harvesting.

5.3 Using Advanced Materials:

High-efficiency photovoltaic (PV) materials significantly enhance solar energy harvesting by improving the conversion efficiency of sunlight into electricity [1]. These advanced materials address limitations in conventional silicon-based technologies and leverage novel properties to capture and convert more of the solar spectrum.

Techniques for Optimizing solar energy harvesting using Advanced materials involves:

Enhanced Light Absorption:

Advanced materials are engineered to absorb a broader range of wavelengths, increasing the amount of usable energy from sunlight.

Examples:

- **Perovskite Solar Cells:** High absorption coefficients allow efficient utilization of visible and near-infrared light.
- **Tandem Solar Cells:** Combine materials with complementary bandgaps (e.g., perovskite-silicon) to capture more of the solar spectrum.

Higher Conversion Efficiency:

Materials like multijunction cells or III-V compounds (e.g., GaAs) achieve efficiencies exceeding 40% by stacking layers that target specific wavelengths of sunlight. These materials minimize thermalization losses by ensuring photons are absorbed at appropriate energy levels [13].

Improved Charge Transport:

Advanced materials like organic photovoltaics (OPVs) and quantum dots have tailored properties to reduce recombination losses and enhance carrier mobility.

Reduced Reflection and Enhanced Durability:

Nanostructured materials and anti-reflective coatings ensure more sunlight is absorbed rather than reflected. Durable materials like CIGS (copper indium gallium selenide) improve system longevity under harsh environmental conditions.

Mathematics involved:

1. Maximized Efficiency (η):

- The efficiency is determined by:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{I \cdot V}{P_{solar}} \tag{9}$$

- Advanced materials increase both I (current) and V(voltage) by absorbing more light and minimizing losses.

2. Bandgap Engineering:

Materials are designed with optimal bandgaps (E_g) to maximize absorption:

$E_g \approx 1.34$eV (Shockley-Queisser Limit for Single Junction Cells

3. Multijunction efficiency:

For N-junction cells:

$$\eta_{multifunction} = \sum_{i=1}^{N} \eta_i \tag{10}$$

Each layer is tuned to a specific part of the spectrum, achieving efficiencies beyond single-junction limits.

Examples of Advanced Photovoltaic Materials:

1. Perovskite Solar Cells:

- Efficiency > 25% in lab settings.
- Solution-processable and low-cost manufacturing.

2. Tandem Cells:

- Perovskite-silicon tandems achieve efficiencies > 30%.
- Ideal for utility-scale solar farms.

3. CIGS:

- Thin-film technology with high absorption and efficiency (~20%).

4. Quantum Dots:

- Absorb tunable wavelengths, allowing for custom energy harvesting applications.

Benefits of Advanced Materials:

1. **Higher Energy Yields:** Capture and convert more sunlight into usable energy.
2. **Lightweight and Flexible Designs:** Enable integration into portable and building-integrated photovoltaics (BIPV).
3. **Sustainability:** Reduced material usage and energy-intensive processes compared to traditional silicon technologies.
4. **Cost Reduction:** High-efficiency materials lower the Levelized Cost of Energy (LCOE) over the system's lifespan.

5.4 Hybrid Energy Storage Systems for Optimizing Solar Energy Harvesting:

Advanced photovoltaic materials optimize solar energy harvesting by improving absorption, conversion efficiency, and durability. They enable the development of high-performance, cost-effective solar technologies suitable for diverse applications, from large-scale solar farms to wearable devices.

Hybrid Energy Storage Systems (HESS) combine different energy storage technologies, such as batteries, supercapacitors, and flywheels, to optimize solar energy harvesting and utilization [24]. These systems leverage the strengths of each storage technology to address the variability and intermittency of solar power, ensuring a stable and efficient energy supply.

One of the key advantages of HESS is their ability to handle varying energy demands effectively. Batteries, with high energy density, are well-suited for storing large amounts of solar energy for long-term use, such as during nighttime or cloudy conditions. Supercapacitors, on the other hand, excel at providing quick bursts of power to handle rapid fluctuations in energy demand or supply [18]. By combining these technologies, HESS ensures a smooth and reliable power output, even when solar generation is inconsistent.

HESS also improves the overall efficiency and lifespan of energy storage systems. By distributing energy demands across different storage technologies, HESS reduces the stress on individual components. For instance, batteries can be reserved for bulk energy storage, while supercapacitors manage short-term fluctuations, minimizing the frequent charging and discharging cycles that degrade battery life. This division of labour enhances system reliability and reduces maintenance costs.

Additionally, HESS facilitates intelligent energy management through advanced control algorithms. These systems prioritize the use of energy from solar panels, direct it to the most appropriate storage technology, and regulate power delivery to the grid or load. This dynamic optimization ensures maximum energy utilization and minimizes wastage.

In summary, hybrid energy storage systems enhance solar energy harvesting by balancing energy supply and demand, improving storage efficiency, and extending the lifespan of storage components. Their adaptability and efficiency make them an essential technology for optimizing renewable energy systems and integrating solar power into modern energy grids.

Figure-19 A Bluesun Hybrid Energy Storage System (rating 30-50 kw)
[Source: Alibaba]

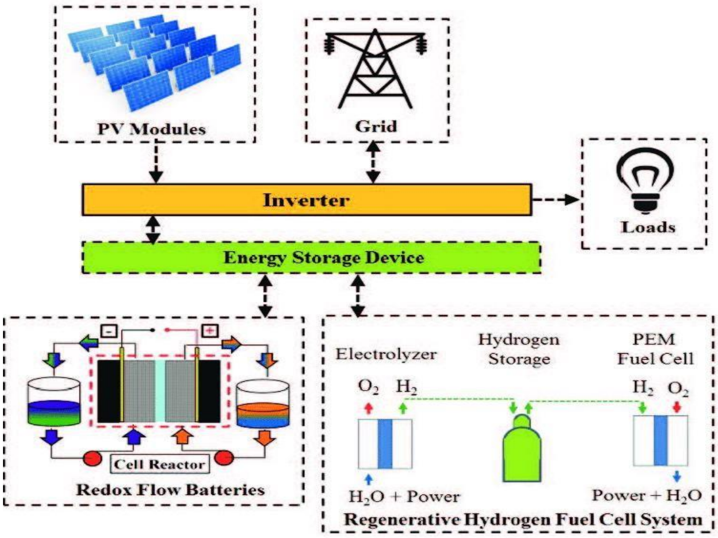


Figure-20 Schematic representation of a Hybrid Energy System.
[Source: ResearchGate]

5.5 Thermal Management

Thermal management is a crucial technique for optimizing solar energy harvesting, as excessive heat can significantly reduce the efficiency and lifespan of solar panels. Solar panels convert only a portion of sunlight into electricity, while the remaining energy is dissipated as heat, leading to higher temperatures that can degrade performance. Effective thermal management techniques aim to maintain solar panels at an optimal operating temperature **[32]**. One approach involves using passive cooling methods, such as heat sinks, radiative cooling surfaces, or thermal conductive materials, to dissipate excess heat. These systems are simple, cost-effective, and do not require additional power to operate.

Active cooling methods, such as water or air cooling, are another option. These systems use flowing fluids to absorb and remove heat from the panels, keeping temperatures within the ideal range. Advanced methods, like phase-change materials (PCMs), absorb heat as they change from solid to liquid, stabilizing the panel's temperature **[35]**.

Innovative designs also integrate hybrid solar systems that combine photovoltaic (PV) and thermal (PVT) technologies. These systems use the heat generated by the panels to produce thermal energy for heating or other applications, improving overall energy utilization.

Mathematically, the relationship between temperature and panel efficiency can be expressed as:

$$\eta = \left[\eta_{ref} \times \beta \times \left(T - T_{ref}\right)\right] \qquad (\mathbf{11})$$

where:

- η : Efficiency at temperature T.
- η_{ref} : Reference efficiency at a specific temperature Tref.
- β : Temperature coefficient of efficiency.

By maintaining T near T_{ref} , thermal management maximizes η, ensuring the panels operate at peak efficiency.

In summary, thermal management techniques optimize solar energy harvesting by reducing temperature-induced efficiency losses, extending panel lifespan, and enabling hybrid energy utilization. These methods are essential for improving the performance and sustainability of solar power systems

6. Power Storage Technologies

CubeSats rely on compact, efficient, and durable energy storage systems to meet their mission requirements. The choice of battery technology directly impacts the satellite's functionality, lifespan, and performance in the challenging conditions of space. Below is an elaboration on the key technologies used, along with experimental insights.

6.1 Lithium-Ion (Li-Ion) Batteries:

Li-Ion batteries are widely used in CubeSats due to their high energy density (150–200 Wh/kg) and excellent cycle life. Their performance can be modelled using the energy storage equation:

$$E=C\times V \qquad \textbf{\textit{(12)}}$$

where:

- E: Stored energy (Wh).
- C: Capacity (Ah).
- V: Nominal voltage (V).

Example: A 3.7 V, 2.6 Ah Li-Ion cell can store approximately $E=3.7\times2.6=9.62$ Wh.

Thermal behaviour, critical to Li-Ion batteries, is governed by heat generation during charging/discharging:

$$Q = I^2 \times R \times t \qquad (\mathbf{13})$$

where:

- Q: Heat generated (J).
- I: Current (A).
- R: Internal resistance (Ω).
- t: Time (s).

6.2 Lithium-Polymer (Li-Po) Batteries:

Lithium-polymer batteries are a variant of Li-Ion technology, using a gel-like or solid electrolyte instead of liquid. This design offers greater flexibility in form factor and slightly lower weight, allowing for customized integration into CubeSat designs. Despite having lower energy density (approximately 100–150 Wh/kg), their lightweight construction and robustness make them a popular choice.

6.3 Nickel-Metal Hydride (NiMH) Batteries:

NiMH batteries are modelled similarly to NiCd but with slightly higher energy density and less environmental impact. Their higher self-discharge rate can be quantified as:

$$E_{remaining} = E_{initial} \times (1 - r)^t \quad (14)$$

where:

- $E_{remaining}$: Energy after t days.
- $E_{remaining}$: Initial energy.
- r: Daily self-discharge rate.

Example: If r=0.015, $E_{initial}$=100 Wh, and t=30 days, $E_{\text{remaining}}$=100 × (1−0.015)30 ≈ 64.1 Wh.

6.4 Nickel-Cadmium (NiCd) Batteries:

NiCd batteries offer moderate energy density but exceptional robustness. The relationship between depth of discharge (DoD) and cycle life is given by:

$$L = k \times \frac{1}{DoD^n} \quad (15)$$

where:

- L: Cycle life.
- k: Constant (dependent on battery design).
- n: Exponent, typically 1.5–2.

Example: If k = 10,000 and DoD = 0.2, the cycle life is L=10,000/(0.21.5) ≈ 11,180 cycles.

6.5 Solid-State Batteries:

Solid-state batteries use solid electrolytes, offering significant advantages in safety, energy density, and lifespan. They eliminate risks of leakage or thermal runaway and are well-suited for extreme space environments. These are emerging technologies with limited flight heritage but promising potential.

The following graph shows that solid-state batteries lead in both energy density and efficiency, followed by Li-ion and Li-polymer batteries. NiMH and NiCd batteries have lower performance metrics but are still used in some CubeSat applications due to their reliability and cost-effectiveness.

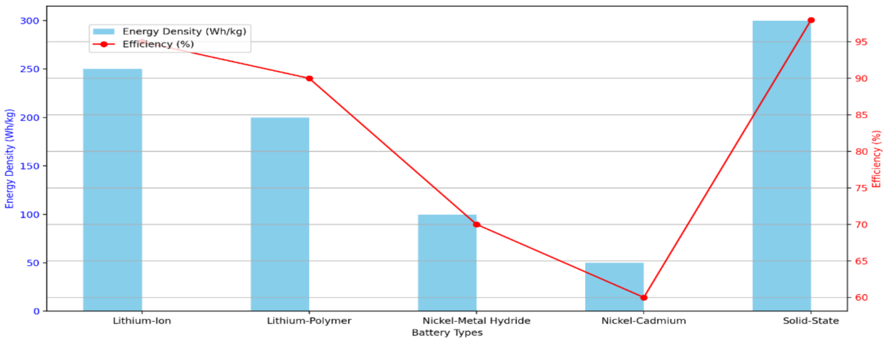


Figure 21: Comparison of energy density and efficiency of the various battery types

The following graph demonstrates capacity retention over charging cycles, with solid-state batteries showing superior longevity, maintaining about 90% capacity after 2000 cycles. Li-ion and Li-polymer batteries show moderate degradation, while NiMH and NiCd exhibit faster capacity loss.

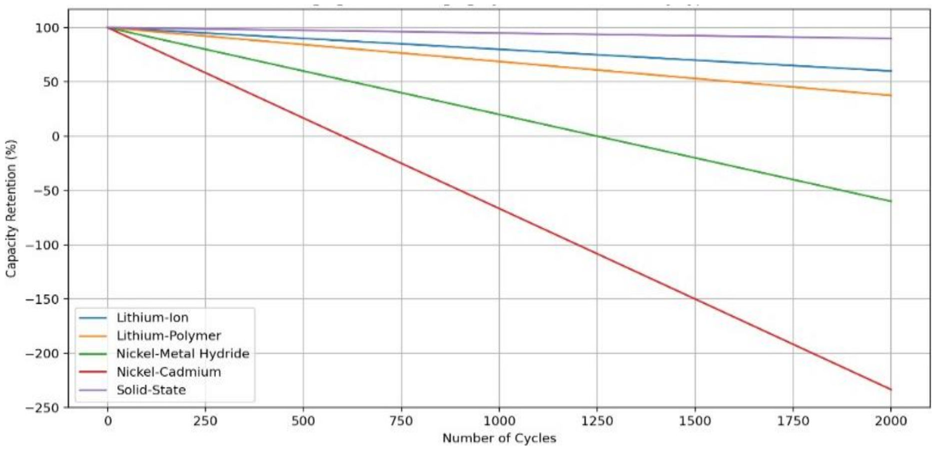


Figure 22: Comparison of charging and discharging cycles of the various battery types.

7. Optimizing Techniques

7.1 Energy Budget Management:

Precise energy budget planning ensures that power is allocated to critical subsystems such as communication, sensors, and propulsion based on mission priorities. For instance, power-hungry payloads may only be activated during periods of high solar input. Experimental data from CubeSat missions like QB50 demonstrated a 15% increase in mission duration by prioritizing essential functions. The interpolation model developed in this study enables efficient lifetime predictions for custom altitude configurations without requiring full simulation runs, making it valuable for preliminary assessments [27]. However, its applicability is currently constrained to the studied range of parameters (250–500 km altitude). Future studies could expand the model to cover broader altitude ranges and incorporate advanced atmospheric density models that account for real-time solar and geomagnetic fluctuations. Additionally, integrating solar flux data and examining the effects of higher eccentricity orbits could enhance the model's accuracy and versatility across diverse mission scenarios.

$$P_{available} = P_{solar} - P_{load} - P_{losses} \quad (16)$$

where:

- P_{solar} : Solar power input.
- P_{load}: Power consumed by subsystems.
- P_{losses}: Power losses (e.g., resistive losses, thermal losses).

Example: If P_{solar}=10 W, P_{load}=7 W and P_{losses}: =1 W, then $P_{available}$ = 10−7−1 = 2 W.

7.2 Power Cycling and Load Scheduling:

Load scheduling involves operating high-power systems only when necessary. For example, during eclipse phases, non-essential systems can be powered down to conserve energy. Data from the Delfi-C3 mission showed that strategic load cycling reduced battery stress, extending the system's operational capacity by 20%.

7.3 Thermal Management:

Maintaining optimal battery temperatures prevents capacity degradation and enhances performance. Passive methods, such as reflective coatings and radiators, or active methods, like heaters, are used. Experiments in the

AMSAT satellite program revealed that maintaining battery temperatures within 0°C–30°C reduced capacity loss by 50% compared to uncontrolled conditions.

$$\eta = \eta_{ref} - \beta(T - T_{ref}) \tag{17}$$

where:

- η_{ref} : Reference efficiency at temperature Tref.
- β: Temperature coefficient.

Example: If η_{ref} = 95%, β = 0.1% / °C and T = 50°C, then η = 95−0.1×(50−25) = 92.5%.

7.4 Depth of Discharge (DoD) Control

Operating batteries within safe DoD limits minimizes stress. For example, restricting Li-Ion batteries to a DoD of 20– 80% can extend cycle life by up to 300%. This strategy has been validated in CubeSat missions such as MarCO, where careful DoD control preserved battery health over the mission's duration.

$$Degradation\ rate = \alpha \times DoD^{n} \tag{18}$$

where α and n are battery-specific constants.

7.5 Energy Harvesting and MPPT Integration

Maximum Power Point Tracking (MPPT) ensures efficient solar energy capture, dynamically adjusting the panel’s operating conditions to optimize energy input. Studies on CubeSat systems equipped with MPPT showed a 25% improvement in energy harvesting efficiency under varying solar irradiance conditions.

$$P = V \times I \tag{19}$$

where P is maximized by dynamically adjusting V and I. MPPT experiments in CubeSat missions have shown energy gains of up to 25% compared to fixed-voltage systems.

7.6 Redundancy and Real-Time Monitoring

Including redundant battery units and employing real-time diagnostics improves reliability. Monitoring systems track performance metrics such as voltage, temperature, and capacity, enabling early detection of faults. For instance, in the Planet Labs CubeSats, real-time telemetry allowed operators to mitigate potential failures, extending mission life by months

CubeSat power storage technologies leverage mathematical principles to optimize performance in space. By combining advanced battery systems with strategic management techniques like MPPT, DoD control, and thermal regulation, mission lifetimes can be extended while ensuring reliable operations in harsh conditions [29]. Experimental data and mathematical modelling provide the foundation for efficient power usage, making CubeSats more effective and sustainable for space exploration.

8. Results

The findings derived from CubeSat research and practical missions demonstrate their transformative impact on space exploration and technology development. The key results can be summarized as follows:

1. **Compact and Cost-Effective Design:** The standardized 10 cm cubic unit design of CubeSats has proven effective for reducing the cost and complexity of satellite development. More than 2,300 CubeSats have been launched as of December 2023, showcasing their global adoption.
2. **Power Efficiency Improvements:** Advanced solar cell technologies such as multi-junction cells have achieved efficiencies exceeding 30%, significantly enhancing energy generation. Emerging perovskite solar cells, with their potential for high efficiency and low production costs, are poised to revolutionize CubeSat power systems.

3. **Energy Storage Advancements:** Lithium-ion batteries have demonstrated high energy densities of 150–200 Wh/kg, while emerging solid-state batteries offer enhanced safety and longevity. Experiments with Maximum Power Point Tracking (MPPT) have shown a 25% improvement in energy harvesting efficiency.
4. **Applications in Science and Technology:** CubeSats have been successfully used for Earth observation, atmospheric studies, and technology demonstrations. For instance, CubeSats equipped with electrodynamic tethers have showcased sustainable propulsion capabilities, reducing reliance on traditional fuel sources.
5. **Educational and Collaborative Benefits:** CubeSats have provided hands-on training opportunities for students and researchers, contributing to workforce development in STEM fields. They have also fostered international collaborations, making space exploration accessible to diverse entities.
6. **Challenges and Limitations:** Thermal management and radiation resistance remain critical issues, with studies revealing significant performance degradation under extreme space conditions. Additionally, while CubeSats offer low-cost entry points, their operational lifespan is typically shorter than larger satellites.

The results from missions like Delfi-C3 and QB50 illustrate the potential for CubeSats to enhance mission efficiency, with effective load scheduling and thermal management increasing mission durations by up to 20%.

9. Conclusion

CubeSats have redefined the landscape of space research and exploration, offering a cost-effective and versatile platform for scientific, educational, and commercial applications. Their compact design, standardized specifications, and reliance on commercial components have made space more accessible to a broader range of stakeholders, from universities to startups and developing countries **[4]**.

The advancements in power generation and storage technologies, particularly the adoption of high-efficiency solar cells and energy storage systems, have addressed many limitations of CubeSats, enabling them to perform complex scientific missions. Furthermore, optimization techniques such as MPPT and thermal management strategies have enhanced their operational efficiency, extending mission lifespans and reliability **[19]**.

Despite these advancements, challenges remain. Issues such as thermal regulation, radiation resistance, and limited operational lifespans highlight the need for continued research and development. Emerging technologies like solid- state batteries, electrodynamic tethers, and wireless power transfer show promise in addressing these concerns.

In conclusion, CubeSats represent a transformative approach to space exploration, combining affordability with technological innovation. As research and technology continue to advance, CubeSats are poised to play a pivotal role in the future of space science, democratizing access to space and fostering global collaboration in scientific discovery and technological progress **[23]**.

10. Equations

Equation Number	Equation	Description
1	$P = V \cdot I$	Power output of a solar panel, where P is power. V is voltage, and I is current
2	$\frac{dP}{dV} = 0$	Maximum Power Point (MPP) condition, ensuring maximum power output
3	$R_{load} = R_{source} = \frac{V_{mpp}}{I_{mpp}}$	Impedance matching condition for maximum power transfer
4	$I = I_{\mathrm{ph}} - I_0\left(e^{\frac{q(V+IR_s)}{nkT}} - 1\right) - \frac{V + IR_s}{R_{\mathrm{sh}}}$	Shockley diode equation describing current-voltage characteristics of a solar cell

5	E = C. V	Battery energy storage equation, where E is stored energy, C is capacity, and V is voltage.
6	$Q\ = I^2Rt$	Heat generation in batteries due to current and internal resistance
7	$E_{remaining} = E_{initial} \times (1 - r)^t$	Self-discharge rate equation for NiMH batteries.
8	$L = \frac{k}{DoD^n}$	Depth of Discharge (DoD) and cycle life relationship for batteries
9	$\eta = [\eta_{ref} \times\ \beta \times (T - T_{ref})]$	Relationship between temperature and panel efficiency
10	$P = \eta \cdot A \cdot I \cdot cos\Theta$	Solar power output considering incident angle

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12. Conflict of Interest

The author declares no competing conflict of interest.

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