Solar Cells in Aerospace Engineering: A Comprehensive Review of Technologies and Applications

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ABSTRACT

Solar cells are the cornerstone of energy generation in aerospace engineering, providing reliable power for satellites, spacecraft, and emerging solar-powered platforms. This review explores the evolution and application of photovoltaic technologies in the aerospace sector, beginning with early silicon devices and advancing to state-of-the-art III–V multijunction, thin-film, and perovskite-based solar cells. Each technology is examined in terms of efficiency, specific power, radiation tolerance, mechanical robustness, and adaptability to the harsh space environment. Comparative analyses highlight the trade-offs among different cell types, while special emphasis is given to recent innovations leveraging nanotechnology to enhance performance and resilience in orbit. By synthesizing current research and future prospects, this article underscores the pivotal role of solar cells in enabling sustainable aerospace missions and outlines pathways toward next-generation photovoltaic systems for space exploration.

Keywords: Aerospace Engineering, Solar Cells, Photovoltaic Technologies, Nanotechnology, Space Applications

1. *INTRODUCTION*

1. *The aerospace industry relies fundamentally on reliable, high-performance power sources. Solar photovoltaic (PV) cells are the primary means of electrical power generation for satellites, space probes, high-altitude platforms, and increasingly, for future missions to the Moon, Mars, and beyond[1]. The extreme environment of space vacuum, intense radiation, wide temperature swings, micrometeoroids places stringent requirements on solar cell technology, motivating continuous innovation in materials, design, and testing. This review addresses the types of solar cells used in aerospace, current developments, challenges, and emerging directions[2].*

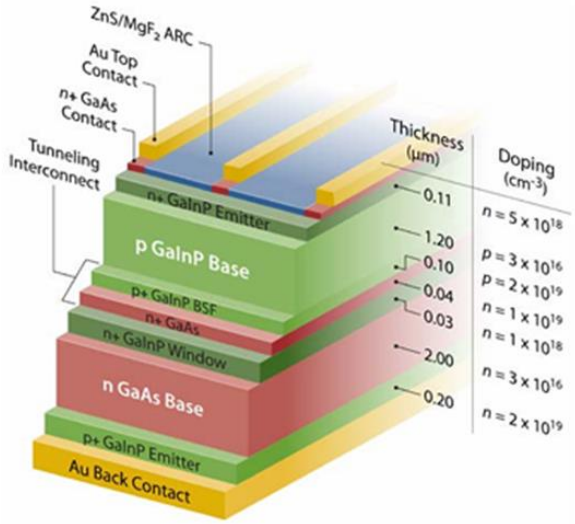


Fig 1: *Schematic of the Ga0.5In0.5P/GaAs tandem solar cell analyzed in this study[3].*

2. Traditional semiconductor solar cells (eg. silicon and III-V compound semiconductors) have been mainstays of space PV systems. Among these, multijunction III-V cells (such as GaInP/GaAs/Ge) offer high conversion efficiencies under AM0 (Air Mass Zero) spectra and good radiation tolerance, making them standard in many spacecrafts' solar arrays[4] . However, trade-offs remain among efficiency, mass (specific power), cost, and durability.
3. Thin-film solar cell technologies (e.g. CdTe, CIGS, amorphous silicon) have been explored for aerospace applications because of their potential advantages in low mass, flexibility, and manufacturability. Early works, such as the review of radiation resistance of thin-film cells by Woodyard & Landis, compare damage under electron and proton irradiation, and conclude that in certain cases thin films degrade less severely than crystalline silicon under equivalent doses[5] .
4. For example, the AlSat-1N CubeSat mission carried CdTe thin-film PVs on ultra-thin glass to assess performance over three years in Low Earth Orbit (LEO). The cells showed stability in many parameters (no delamination, stable short circuit current, series resistance), though some decrease in fill factor and shunt resistance were observed possibly due to diffusion effects under irradiation [6].
5. Another aspect of aerospace solar cell development is in III-V multijunction cells with newer fabrication techniques aiming to reduce cost while preserving or improving performance. For instance, Schulte et al. (2018) reported Ga0.5In0.5P/GaAs tandem cells grown by dynamic hydride vapor phase epitaxy (D-HVPE), yielding ~23.7% efficiency with good fill factor, along with modeling that shows a path toward ~30% when optimizing emitter designs [7].

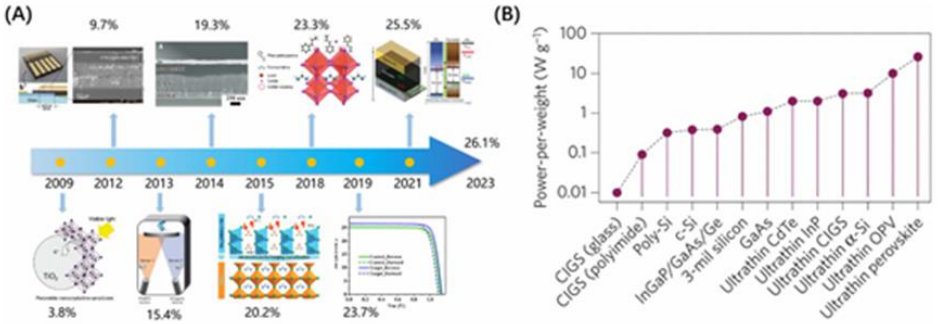


Fig 2: A) Schematic of the rapid development of PCE for PSCs. (B)Comparison of the power-to-weight ratio of common solar cells[8].

6. Multijunction cell architectures continue to evolve. Recent developments include cells combining GaAs with lower-bandgap layers, or even coupling GaAs with CIGSe, yielding very high efficiencies

under low concentration sunlight[9] . These combinations aim to maximize spectral utilization while reducing weight, cost, and resource use.

7. Alongside efficiency, radiation resistance is critical. Ionizing radiation and displacement damage from protons, electrons, x-rays are among the chief degraders. Studies such as ionizing radiation effects on CIGS cells show that these types of thin films display modest degradation under x-ray exposure, with potential recovery after annealing[10] . Similar studies on silicon and GaAs thin film variants show varied response depending on defect generation and minority carrier lifetimes[11] .

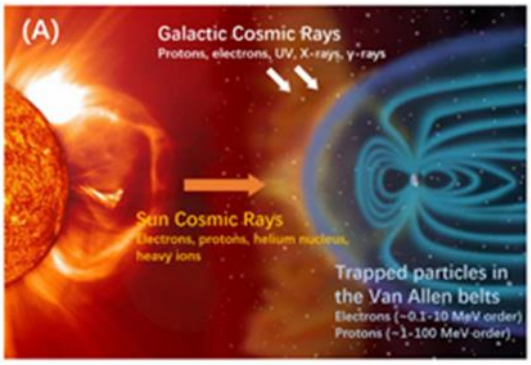


Fig 3: (A) Schematic view of the Van Allen belts, SCRs, and GCRs[8].

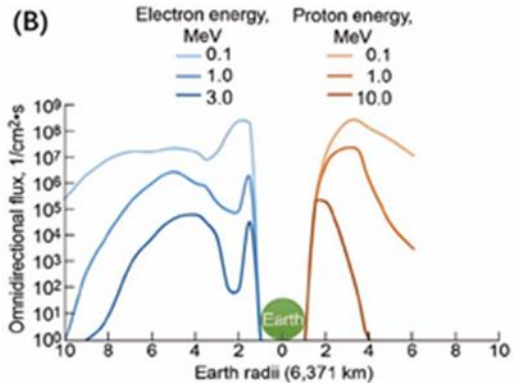


Figure 4: Flux of electron and proton radiation around the Earth[8].

8. III-V multijunction cells are favored also because of their relatively high tolerance to radiation damage. A brief review of high efficiency III-V solar cells for space application outlines how radiation damage evaluation models (such as equivalent fluence and displacement damage dose) are being used to quantify and compare performance under different irradiation scenarios[12] .
9. Meanwhile, toward newer “third-generation” PV technologies, perovskite solar cells (PSCs) are gaining attention for space use. Their low weight, high specific power, and flexibility are attractive. A recent review, *Perovskite Tandem Solar Cells for Low Earth Orbit Satellite Power Applications* (2024), summarizes progress on PSCs with emphasis on tandem devices (e.g. 2-terminal perovskite-based tandems) for LEO, along with challenges like stability, encapsulation, thermal cycling, and radiation resistance[13].
10. A companion review, *Advancements in radiation resistance and reinforcement strategies of perovskite solar cells in space applications* (2024), focuses explicitly on strategies to improve PSCs’ endurance against various space environmental stressors (electrons, protons, UV, etc.) and suggests design methods (buffer layers, self-healing compositions, advanced encapsulation) to mitigate degradation[14] .
11. Importantly, another recent work *Space Environment Considerations for Perovskite Solar Cell Operations: A Review* (2025) catalogs and compares environmental stressors across orbital regimes (LEO, GEO, lunar, interplanetary) and how PSCs respond in each case—thermal extremes, vacuum, radiation, gaseous contamination, etc. [15]. These comparisons help frame requirements and highlight gaps in current testing.

12. Effective calibration and standardized testing conditions are also necessary to reliably evaluate new solar cell technologies for aerospace. The article *Calibration for Space Solar Cells: Progress, Prospects, and Challenges* (2024) examine measurement and calibration techniques (AM0 spectra, etc.), discussing how differences in testing protocols can lead to discrepancies in reported performance, especially for novel technologies like PSCs and organic PVs [16].
13. Despite their promise, PSCs still lag behind in long-term operational stability compared to silicon and III-V cells. Issues such as thermal cycling, ion migration, UV-induced degradation, and mechanical stress from mismatch in thermal expansion remain obstacles, as outlined in design strategy studies [17].
14. Another axis of innovation has been in novel architectures and hybrid devices. Tandem solar cells—either III-V/Si or perovskite/Si—are of high interest both in terrestrial PV and aerospace. A comprehensive review comparing tandem solar cells integrated on silicon substrate (III-V vs perovskite) underscores trade-offs among achievable efficiency, manufacturing complexity, cost, and durability[18] .
15. In sum, the diversity of solar cell types in aerospace—crystalline silicon, III-V multijunction, thin films (CdTe, CIGS, amorphous Si), perovskites and hybrid/tandem devices—reflects a balance among efficiency, specific power, radiation tolerance, mass, and cost. The subsequent sections of this review will systematically survey these types: their operating principles; performance in space; degradation mechanisms; design and engineering strategies; and emerging directions toward achieving lighter, more durable, efficient, and cost-effective solar cells for aerospace missions[19].

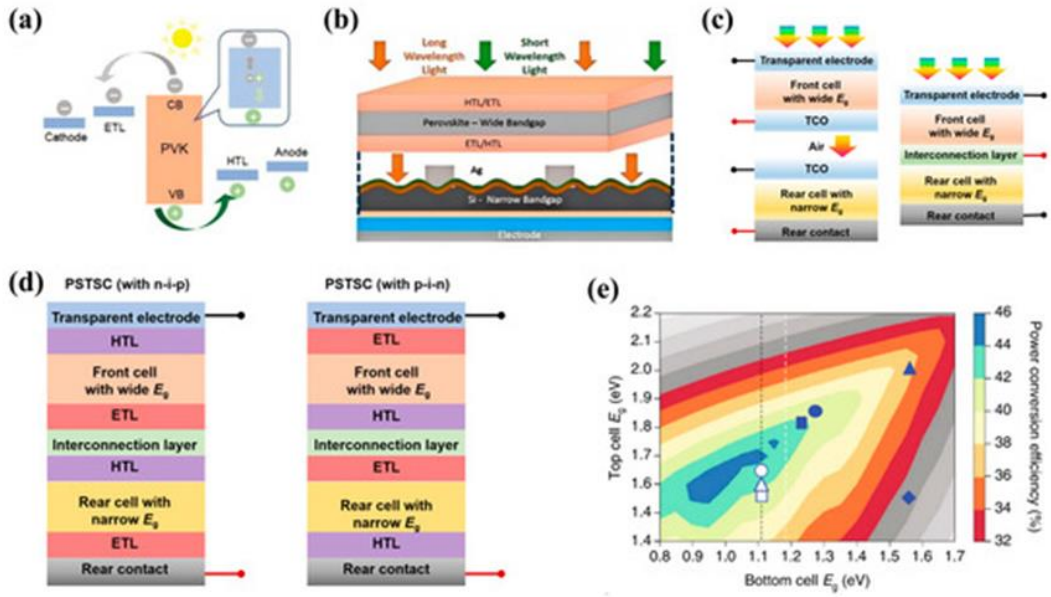


Figure 5: (**a**) Working mechanism of PSCs. (**b**) Schematic diagram of the working principle of PSTSCs. (**c**) The device configuration of 4-T and 3-T PSTSCs. (**d**) The n-i-p and p-i-n 2-T PSTSCs. (**e**) Theoretical efficiency limit for 2T tandems [20].

Examination & comparison of solar-cell types used in aerospace

Overview — what will be compared

For each solar cell class below, I examine: physical/material basis; beginning-of-life (BOL) efficiency and typical end-of-life (EOL) behavior; radiation tolerance; specific power (W/kg) or mass considerations; thermal and mechanical performance; maturity/flight heritage and typical aerospace applications; manufacturability and cost considerations; and key limitations and mitigation strategies. Key comparative statements are cited with the most relevant literature[21].

1) Crystalline Silicon (c-Si) cells (space and terrestrial variants)

Material / principle: single-crystal or Mult crystalline silicon p-n junction devices adapted for space (often with cover glass, anti-reflective/coatings). Historically earliest PV used in space[22].

Performance & specific power: terrestrial high-efficiency silicon (heterojunction / IBC) reach ~24–27% at AM1.5 but standard space BOL silicon cells are typically lower; for small satellites, high-efficiency silicon variants can be used but their power-to-mass is generally lower than III-V multijunction when cover glass and harness are included[23].

Radiation tolerance & degradation: silicon suffers displacement damage (protons, electrons) producing carrier lifetime loss; degradation is greater per unit fluence than for well-designed III-V cells, making Si less favored for high-radiation or long-duration missions unless heavily shielded or replaced in design tradeoffs. Models of displacement-damage dose and equivalent fluence are standard for projecting Si degradation.

Thermal / mechanical: silicon has well-known thermal coefficients and mechanical robustness but can be heavy when mounted on rigid substrates; thermal cycling leads to mechanical stress at interfaces[24].Maturity & uses: long flight heritage (early satellites, some terrestrial-derived arrays); used sometimes in CubeSats and near-Earth small missions when cost is primary and radiation exposure limited. Main limitations & mitigations: lower radiation tolerance and specific power vs III-V; mitigations include thicker cover glass, radiation-hard silicon processing, or choosing applications with benign radiation environments[25].

2) Single-junction III-V (GaAs, InP) cells

Material / principle: direct-bandgap III-V semiconductors (GaAs, InP) with superior radiation response and higher single-junction efficiencies than Si at AM0.Performance & specific power: GaAs single-junction cells typically exhibit higher BOL efficiencies (~20–30% for optimized space variants) and better specific power (W/kg) when implemented in thin-film or epitaxial lift-off formats. Radiation tolerance & degradation: GaAs shows better displacement damage tolerance than silicon; InP can be even more radiation-tolerant for electron/proton environments. Radiation modelling and empirical testing (proton/electron irradiation) are used to predict EOL performance[26].

Thermal / mechanical: good performance across broad temperature ranges, but thermal expansion mismatch with substrates and interconnects must be managed. Thin, flexible III-V approaches reduce mass and improve deployment options.

Maturity & uses: widespread in spacecraft, including large arrays and small sats; GaAs has a strong flight heritage (e.g., Juno used GaAs + Si combinations in its arrays)[27].

Limitations & mitigations: cost is higher than Si; techniques such as epitaxial lift-off, ultrathin cells, and metamorphic architectures help reduce mass/cost while keeping radiation hardness.

3) III-V Multijunction Cells (GaInP/GaAs/Ge and variants)

Material / principle: stacked p-n junctions (tandem) each tuned to a portion of the solar spectrum (3-junction typical; 4+ junctions in high-end devices) — the standard for high-performance space PV[28].

Performance & specific power: highest terrestrial and space BOL efficiencies among practical cells (30%+ at AM0 for triple-junction and >30% for advanced 4-junctions). End-of-life efficiencies remain high due to radiation tolerance; specific power (W/kg) is excellent when cells are made ultrathin and integrated in lightweight arrays[29].Radiation tolerance & degradation: III-V multifunction's are among the most radiation-tolerant. Standard radiation-damage models (NRL displacement damage dose, JPL equivalent fluence) are used to predict degradation; empirical tests show comparatively smaller relative degradation after proton/electron exposure than Si[14].

Thermal / mechanical: layered structure can complicate thermal behavior; metamorphic and lattice-mismatched approaches allow bandgap tuning but require careful stress/defect control. High-temperature near-Sun missions need specific designs (HIHT)[30].Maturity & uses: predominant in GEO telecom, high-power LEO missions, and more recently in small sats seeking compact, high-power arrays. AZUR and other vendors provide flight-qualified triple-junction cells with well-documented BOL/EOL characteristics. Juno's arrays (to Jupiter) leveraged advanced high-efficiency cells and modeling. Limitations & mitigations: high cost and complex fabrication; recent advances in dynamic HVPE and 4-junction designs and ultrathin formats mitigate weight/cost tradeoffs[31].

4) Thin-film chalcogenides (CIGS, CdTe)

Material / principle: Cu (In, Ga) Se2 (CIGS) and CdTe are thin-film absorbers deposited on rigid or flexible substrates; good absorption per unit thickness enables light, flexible arrays[32].Performance & specific power: laboratory efficiencies for CIGS and CdTe have reached

>20%; flexible module implementations yield high specific power (W/kg) because substrate and packaging can be optimized for low mass[33].Radiation tolerance & degradation: CIGS and some thin films have shown favorable radiation behavior in certain tests; CIGS in particular can be relatively resilient to displacement damage (some NASA tests support this), though results vary by fabrication and substrate. CdTe has commercial maturity and decent behavior under certain exposures, but encapsulation in vacuum and UV/thermal cycling are key issues. Thermal / mechanical: flexible thin films tolerate bending and enable deployable arrays and conformal panels for small satellites and high-altitude platforms. However, thermal cycling and vacuum outgassing/encapsulation must be addressed[34].Maturity & uses: CIGS thin films have been flown/tested on small spacecraft and are promising for flexible rollable arrays; CdTe is mainly terrestrial in commercial deployment but has been studied for space via test flights. NASA and other agencies have performed environmental tests and small flight experiments[35].Limitations & mitigations: variability in space radiation response and long-term stability vs III-V; robust encapsulation, selection of flexible substrates that survive launch/TVAC, and targeted radiation testing mitigate risks[36].

5) Amorphous Silicon (a-Si) and other amorphous thin films

Material / principle: hydrogenated amorphous silicon and related thin films; lighter and flexible but lower efficiency and light-induced degradation (Staebler–Wronski effect).

Performance & specific power: lower efficiency (~6–12% typical in practice), but very low mass per area when implemented as flexible films; niche uses where low cost and flexibility trump efficiency[37].Radiation tolerance & degradation: a-Si shows complex responses (some tolerance to displacement damage but significant light-induced degradation and potential stability issues under combined environmental stress). Not a frontrunner for long-duration, high-radiation missions. Uses & maturity: experimental and limited flight tests; often superseded by higher performance thin films like CIGS for aerospace use[38].

6) Perovskite Solar Cells (PSCs) — emerging for space

Material / principle: hybrid organic–inorganic halide perovskites (e.g., methylammonium/lead halides) — extremely high absorption coefficient and tunable bandgaps enabling lightweight, high specific power and tandem integration[39].

Performance & specific power: lab single-junction PSCs have reached >25% (terrestrial); perovskite/Si tandems are demonstrating >28% on small cells. In space, their extremely low mass and flexibility translate to very high specific power potential. Radiation tolerance & degradation: recent irradiation studies show perovskites can be surprisingly radiation-tolerant to electrons/protons/γ in the short term, but long-term stability (thermal cycling, vacuum, moisture, UV) and ion migration are major concerns; strategies (encapsulation, compositional engineering, buffer layers, self-healing chemistry) are under active development[40].

Thermal / mechanical: perovskites are mechanically flexible and can be processed on thin substrates; yet thermal stability under HIHT or long vacuum exposure needs engineering countermeasures[41].Maturity & uses: flight-qualification is nascent; several groups and agencies are running LEO test experiments and lab simulations. PSCs are a high-potential research direction for LEO and low-dose missions pending validation. Limitations & mitigations: primary barriers are long-term stability and encapsulation compatible with space; mitigations include robust multilayer encapsulation, mixed-cation perovskites, and tandem integration with stable sub cells[42].

7) Organic Photovoltaics (OPV) and Quantum-Dot PV (QDPV)

Material / principle: organic semiconductors (polymer/fullerene blends, non-fullerene acceptors) and nanocrystal quantum dots. Both are very lightweight and can be fabricated on flexible substrates[43].

Performance & specific power: record lab efficiencies are lower than perovskites/III-V (~15% for OPV, lower for QD tandems), but device weight is minimal, offering interesting specific power at small scales[44].Radiation & environmental tolerance: OPV and QD devices have limited flight heritage and show sensitivity to UV, vacuum, and radiation unless specifically engineered; QD devices may offer improved radiation resilience in some reports but need more validation[45].Maturity & uses: largely experimental for aerospace; promising for disposable/short-duration missions or where extreme conformality and low weight are required[46].

8) Concentrator Photovoltaics (CPV) for space

Principle & performance: optical concentrating optics feeding high-efficiency cells (often III-V multijunction) to increase power per unit cell area; effective where pointing and thermal control are manageable. CPV enables very high cell efficiencies under concentration and can reduce cell area (and therefore mass) but increases tracking/structural complexity[25].Applications & limitations: useful for near-Sun or high-intensity missions and for terrestrial CPV research that informs space designs; however, moving optics, high operating temperatures, and pointing/tracking increase system complexity for spacecraft[47].

9) Architectural & system aspects across cell types

- **Specific power (W/kg)**: thin-film (CIGS, flexible perovskite) and ultrathin III-V arrays excel. Manufacturer datasets and NASA SoA reports quantify that ultrathin MJ cells in lightweight arrays deliver the highest spacecraft-level W/kg in many designs.
- **Radiation modelling & qualification**: common practice uses displacement damage dose and equivalent fluence models (NRL DDD, JPL EF) to translate ground irradiation to on-orbit EOL predictions — these are applied for nearly all space cell qualification programs.[48]
- **Encapsulation & reliability**: long-term space operation hinges as much on encapsulation, interconnect reliability, and array mechanical design as on cell material. New materials (thin glass, flexible laminates, low-outgassing adhesives) have enabled rollable and deployable arrays but require careful qualification.
- **Mission examples**: Juno (deep Jupiter mission) demonstrated feasibility of solar arrays far from the Sun using high-performance cells and careful modeling; CubeSats increasingly use high-efficiency MJ cells or COTS flexible panels depending on mission constraints[49].

Table 1 — Technical snapshot (typical BOL efficiencies, relative radiation tolerance, specific power potential, maturity)[50].

Cell type	Typical BOL efficiency (AM0 / space variants)	Relative radiation tolerance	Specific power potential (qualitative)	Maturity / flight heritage
Crystalline Si	~15–22% (space variants lower than MJ)	Low–moderate (sensitive to displacement damage).	Moderate (limited by substrate/cover glass mass).	Long heritage; early satellites; some small sats.
GaAs (single-junction)	~20–30% (optimized)	Good (better than Si); InP better for some spectra.	High (thin/ultrathin formats).	Wide heritage in satellites; used in many missions.
III-V Multijunction (3J,4J)	30%–>34% (AM0, advanced designs)	Very good; widely used for long missions.	Very high (best W/kg when integrated into lightweight arrays).	State-of-the-art for GEO/HEO/DEEP missions; increasing small sat use.
CIGS thin film	~12–22% (lab); flexible modules variable.	Moderate; some studies show resilience, varies by process.	High (flexible/rollable enable high W/kg).	Flight tests & experiments; NASA studies & small sat tests.
CdTe thin film	~15–20% (lab/terrestrial)	Moderate; encapsulation critical.	High for flexible implementations; module mass varies.	Terrestrial commercial maturity; space tests limited.
a-Si	~6–12%	Variable; light-induced degradation; limited space use.	High (lightweight) but low output per area.	Experimental / limited.

Perovskites	Lab single-junction 20–26%; tandems >28% (terrestrial).	Emerging: short-term radiation tolerance promising; long-term stability unresolved.	Very high (ultra-light flexible devices).	Research to early flight tests / ground qualification efforts.
OPV / QD PV	OPV ~10–15% (lab records); QD lower.	Low–uncertain; QD shows some promising radiation studies but unproven.	Very high (ultra-thin flexible).	Experimental; limited flight tests.
CPV (with MJ cells)	Cell efficiencies under concentration very high (MJ use)	Depends on cell; MJ under concentration still quite good if thermal managed.	Potentially very high system W/kg (if optics lightweight & pointing available).	Mostly terrestrial CPV experience; space CPV concepts studied.

Table 2 — Advantages vs limitations (practical)[50].

Cell type	Key advantages	Key limitations	Typical aerospace mitigations
c-Si	Low cost, well-known processing	Lower radiation resistance, heavier	Use in LEO/short missions; shielded arrays; low-cost small sat builds.
GaAs (1J)	Good efficiency, radiation tolerant	Cost, substrate mass	Thin/epitaxial lift-off, flexible mounting.
III-V MJ	Highest efficiency & EOL performance	High cost, complexity	Use for high-value missions; ultra-thin arrays, vendor qualification (AZUR, Spectro lab).
CIGS/CdTe	Flexible, good W/kg, low material per area	Long-term space reliability variable	Robust encapsulation, preflight irradiation & TVAC testing.
a-Si	Very light, flexible	Low efficiency, Staebler–Wronski degradation	Limited use; specific niche applications.
Perovskites	Very high specific power potential, tandem option	Stability (thermal, ion migration), encapsulation	Compositional engineering, multilayer encapsulation, tandem with stable bottom cells.
OPV/QD	Extremely light & flexible	Low efficiency, stability concerns	Short missions; conformal arrays; rigorous environmental testing.
CPV	Reduces required cell area; enables very high cell efficiency	Tracking, thermal control, optics mass	Use for missions with precise pointing and thermal control; combine with MJ cells.

Table 3 — Readiness & representative references / missions[50].

Cell type	Readiness (TRL rough)	Representative mission / test references
c-Si	TRL 7–9 (space variants)	early satellites; NASA SoA reports.
GaAs (1J)	TRL 7–9	Flight heritage, Juno arrays (GaAs+Si), vendor data (AZUR).

III-V MJ	TRL 8–9	GEO telecom, arrays in LEO, AZUR/Spectro lab/ESA papers.
CIGS	TRL 5–7 (space tests)	NASA CIGS space environment studies; flexible rollable tests.
CdTe	TRL 6–8 (terrestrial high)	NREL CdTe reviews; limited space tests.
a-Si	TRL 4–6	Early experiments; limited modern aerospace usage.
Perovskite	TRL 3–5 (space qualification ongoing)	Lab irradiation tests; recent space environment reviews and pilot LEO tests.
OPV / QD	TRL 3–5	Experimental studies; some ground/stratospheric tests.
CPV (space)	TRL 3–6 (concepts & prototypes)	CPV+MJ concept papers and lab high-concentration MJ results.

Nanotechnology solutions and suggestions to increase solar-cell efficiency for aerospace applications

A. Why nanotechnology for aerospace photovoltaics?

Nano structuring offers multiple levers that are especially valuable for aerospace PV: enhanced light management (trapping, scattering, near-field concentration), spectral control (bandgap engineering, tunable absorption), improved carrier management (reduced recombination via surface/passivation engineering, hot-carrier extraction), and mechanical/weight advantages (ultrathin flexible architectures)[51]. In addition, several nanostructured architectures show improved *radiation tolerance* or recovery mechanisms compared with planar bulk devices a crucial benefit for space missions where displacement damage and ionizing radiation degrade classical PVs .[3]These combined advantages mean nanotechnology can simultaneously raise beginning-of-life (BOL) efficiency, improve end-of-life (EOL) performance, and reduce mass (W/kg) the key aerospace metrics[52].

B. Nanotechnology approaches (mechanisms, evidence, aerospace suggestions)

1) Nanowire and radial-junction architectures — light trapping, thin absorbers, radiation resilience

Mechanism & benefits: Vertically-aligned semiconductor nanowires and radial p–n junctions dramatically increase optical path length via resonant light trapping and waveguiding; they allow very thin absorber volumes while maintaining high absorption, reducing material and mass. Nanowires also decouple optical absorption length from carrier collection length, enabling efficient devices with short carrier diffusion lengths [53].

Radiation behavior: Experimental proton/electron irradiation campaigns show nanowire arrays can tolerate substantially higher damage doses (reported factors ~10–40× better surviving fluence than comparable planar cells in some studies), attributed to reduced volume for damage propagation, radial geometry, and easier annealing/healing of point defects .

Limitations & engineering needs: Surface recombination on high surface-area nanostructures is a major loss channel; robust conformal passivation and contact schemes are essential . Scaling homogeneous, defect-free nanowire arrays to large area, mechanically robust arrays require process control (uniformity, contacting) [20].Aerospace suggestions: Use III-V or InAs/GaAs nanowire multifunction's for missions that need both radiation tolerance and high specific power; apply in ultrathin flexible arrays or foldable/deployable panels. Prioritize in-vacuum thermal cycling and proton/electron irradiation testing of full nanowire array modules, including contacts and encapsulation layers [54].

2) Plasmonic and nanophotonic light-management (metal nanoparticles, gratings, meta surfaces)

Mechanism & benefits: Metallic nanoparticles and engineered nanostructures (plasmonic resonators, dielectric meta surfaces, sub-wavelength gratings) concentrate and redirect light into active absorber layers (near-field enhancement, scattering into guided modes), enabling thinner absorbers while maintaining or increasing absorption[8] . Plasmonics can broaden spectral absorption and enhance coupling into low-absorption bands, particularly helpful for thin films and tandem stacks[55].Radiation behavior & stability: Careful materials choice (noble metals, refractory compounds, or dielectric meta surfaces) is required since nanoscale metals can agglomerate under thermal cycling or degrade if poorly encapsulated. Plasmonic schemes integrated with robust dielectrics or embedded nanoparticles in stable matrices have demonstrated long-term stability in lab studies[56] .Aerospace suggestions: Use plasmonic scatterers or dielectric meta surfaces integrated within thin-film or perovskite stacks to reduce absorber thickness (thus mass) and to increase light harvesting at oblique illumination angles (useful for non-sun-tracking small satellites). Prefer dielectric meta surfaces or encapsulated metal nanostructures with space-rated dielectric coating to avoid metal migration and to manage thermal load [57].

3) Quantum dots and quantum-confined nanostructures — spectral tuning, multiple exciton generation (MEG)

Mechanism & benefits: Quantum dots (QDs) and quantum-confined nanocrystals allow bandgap tunability across the visible/near-IR by size/composition control, enabling spectral matching in tandem architectures and better utilization of the AM0 spectrum. Quantum dots also enable concepts such as multiple exciton generation (MEG) and hot-carrier extraction that, in principle, raise the thermodynamic efficiency limit[58].
Radiation behavior: QD layers are often resilient to displacement damage at the individual nanoparticle scale (smaller defect propagation), and several studies indicate improved retention of open-circuit voltage after irradiation compared with bulk devices; however device architecture and ligands strongly affect performance under irradiation.
Aerospace suggestions: Focus QD research on (a) QD-tuned intermediate band or sub cell layers in tandems, (b) QD sensitizers in robust matrices for flexible arrays, and (c) QDs with radiation-stable surface chemistry (inorganic ligands, crosslinked matrices). Pilot experiments should include high-fluence proton/electron irradiation and post-irradiation annealing studies to characterize defect dynamics[49] .

4) Nanostructured perovskite engineering and protective nanolayers

Mechanism & benefits: Nanoscale compositional engineering (mixed-cation, low-dimensional perovskites, grain engineering) and nanolayered encapsulation (e.g., ALD oxide nanofilms, 2D layered barriers) substantially improve perovskite stability against moisture, ion migration, UV, and thermal stress while preserving high absorption and tunability for tandems. Perovskites' high absorption coefficient enables ultrathin, ultralight devices with exceptional specific power.
Radiation behavior and healing: Recent controlled irradiation experiments show halide perovskites can exhibit defect *healing* or partial recovery under certain irradiation sequences and that nano structuring/compositional choices (e.g., inorganic A-site cations, dimensional reduction) change radiation response favorably. NREL and others demonstrated thin protective coatings that mitigate space-environment damage[51].Aerospace suggestions: Use nanolaminate ALD barriers and atomic-layer passivation on perovskite modules, combine perovskite top cells in tandems over stable bottom cells (e.g., Si or III-V), and plan LEO flight tests with rigorous encapsulation schemes. Design qualification programs to test combined stressors (vacuum, thermal cycling, proton/electron irradiation, UV) because single-stress tests overestimate in-orbit durability.

5) Atomic-level passivation and contact engineering (ALD, core–shell nanowires, ultrathin shells)

Mechanism & benefits: High surface-to-volume ratios of nanostructures make surface passivation essential. Conformal atomic layer deposition (ALD) oxides (e.g., Al_2O_3, TiO_2) or in-situ core–shell growth (e.g., a-Si or oxide shells on Si nanowires) dramatically reduce surface recombination and restore carrier lifetime, boosting device fill factor and efficiency. Advanced contact schemes (transparent conductive oxides on nanostructured textures, conformal metal contacts) reduce series resistance without shading losses.
Aerospace suggestions: Integrate ALD passivation steps into manufacturing flow for nanowire and

thin-film devices; use in-vacuum compatible adhesives and low-outgassing contact materials. Test adhesion and conductivity after thermal cycling and radiation exposure.

6) Nanocomposite encapsulation and thin-film radiation shields

Mechanism & benefits: Nanocomposite coatings (e.g., oxide/graphene multilayers, ultrathin glass with nanolayered diffusion barriers) provide both environmental protection and mitigation against ionizing radiation/atomic oxygen erosion while adding minimal mass. NREL and others have shown ultrathin protective layers substantially improve perovskite survival under simulated space conditions[52].

Aerospace suggestions: Develop ultrathin, multilayer barrier stacks combining inorganic ALD layers and 2D materials (graphene or h-BN) to limit moisture, oxygen and UV ingress and to provide partial radiation damping. Qualification must include micrometeoroid/atomic oxygen exposure for LEO missions and long-duration thermal cycling for GEO/interplanetary missions.

7) Nanophotonic tandems and hot-carrier / intermediate-band concepts

Mechanism & benefits: Nanostructures enable new tandem and hot-carrier architectures: e.g., integrating nanocrystal absorbers as intermediate band layers, or using plasmonic enhancement to extract hot carriers before thermalization. These concepts can raise theoretical conversion limits and enable high efficiency in ultrathin devices.

Limitations & engineering needs: Practical hot-carrier extraction and intermediate band collection require ultra-fast contacts, very careful electronic design, and low recombination — still at research TRL but promising for long-term high-performance space cells.

Aerospace suggestions: Short-term focus on nanostructured tandems (perovskite/Si, QD-tuned sub cells) that are nearer term; longer term invest in hot-carrier/intermediate band demonstrators and correlate device physics with real radiation experiments.

8) Lightweight nanostructured substrates and flexible arrays

Mechanism & benefits: Nanostructured thin glass, polymer substrates reinforced with nanofillers (e.g., nanocellulose, carbon nanotubes) and ultrathin metal foils reduce mechanical mass and enable rollable or deployable arrays, increasing W/kg while easing stowage .

Aerospace suggestions: Combine high-efficiency nanostructured cells with thin glass or reinforced polymer backplanes; ensure outgassing and creep properties meet space standards and validate mechanical robustness under launch vibration and deployment dynamics.

C. Practical implementation recommendations, qualification steps and R&D roadmap

1. **Prioritize cell architectures with near-term flight readiness:** Nanowire-enhanced III-V and nanostructured perovskite tandems (with robust encapsulation) offer the best balance between high specific power and near-term qualification. Plan LEO demonstrators (6–18-month exposures) as the next step to retire key risks[59].
2. **Qualification must test combined stressors:** Perform *combined* vacuum + thermal cycling + proton/electron irradiation + UV + atomic oxygen for LEO (and additional micrometeoroid/hypervelocity tests as appropriate). Single-stressor tests are insufficient to predict in-orbit behavior, especially for soft lattices and organics [8].
3. **Implement conformal atomic-scale passivation and barrier layers in the build flow:** Adopt ALD and other conformal techniques (core–shell nanowire shells, ultrathin oxide barriers) to control surface recombination, block diffusion, and reduce ion migration for perovskites.
4. **Use modular testbeds for rapid iteration:** CubeSat/ESPA carrier flight tests of small nanostructured panels accelerate TRL progression. Include both active telemetry (I–V curves) and material sampling (returnable or post-flight analysis) when possible.
5. **Adopt system-level trade studies that include packaging mass and harness losses:** Gains in cell efficiency can be offset by heavier encapsulation/harnessing; evaluate net spacecraft W/kg and EOL power rather than BOL cell efficiency alone[57] .
6. **Invest in radiation-aware materials science:** Characterize defect formation, migration and healing mechanisms in nanomaterials under energy-tuned irradiation (dual dose methods) to exploit self-healing phenomena observed in perovskites and other soft lattices.
7. **Manufacturability & scale:** R&D should run parallel process-scale studies (large-area ALD, roll-to-roll deposition for nanostructured thin films, uniform nanowire growth) to ensure economical production compatible with aerospace supply chains.

8. **Data sharing & standards:** Establish community radiation-and-environment testing protocols for nanostructured PV (analogous to existing DDD/hardness factor standards) so that results between labs and vendors are comparable and mission designers can rely on published EOL forecasts [55].

Conclusion

Solar cells have become indispensable in aerospace engineering, powering satellites, space probes, space stations, and emerging solar-powered aircraft. The continuous evolution of PV technologies—from early crystalline silicon cells to advanced III-V multifunction's, thin-films, and, most recently, perovskite-based tandems—reflects the sector's need for lightweight, efficient, and radiation-tolerant energy systems. Each solar cell type offers a distinct balance of advantages and limitations, and their selection depends strongly on mission requirements, orbital environments, and cost constraints. Moreover, recent advances in nanotechnology, such as quantum dots, plasmonic structures, and nanostructured coatings, have shown great potential in mitigating space-specific challenges like radiation degradation, thermal cycling, and limited spectral absorption.

Looking ahead, the aerospace industry is likely to embrace hybrid approaches that combine mature, reliable solar cell technologies with cutting-edge nanomaterials to maximize efficiency and durability. Future research should focus on space-relevant testing of emerging materials, integration with high-density storage, and self-healing nanostructures that extend operational lifetimes in harsh orbital environments. As solar energy systems continue to advance, they will play an increasingly central role in enabling sustainable long-duration missions, interplanetary exploration, and potentially space-based solar power systems, strengthening the synergy between photovoltaics and aerospace engineering.

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