

Surveying the potential of flexible and high specific power photovoltaic assemblies and arrays for space applications

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CONTEXT & SCALE

Flexible and lightweight solar arrays offer transformative potential for space missions and services by enabling high specific power, compact stowage, and reliable deployment systems for use in Earth orbits and challenging environments throughout the solar system. The versatility of these arrays to meet the power requirements of diverse mission profiles and spacecraft designs has driven their evolution, from large-scale architectures, such as those on the International Space Station, to compact arrays on current asteroid probes, like the Lucy spacecraft. These advancements have been made possible through the synergy of high-efficiency solar cells and high-performance materials used in photovoltaic arrays and deployment systems. This work presents a comprehensive review of the development of flexible photovoltaic technologies for space applications, highlighting the evolution of solar cells, flexible modules, and arrays through a timeline of key innovations, some of which are documented in patents. A comparative assessment of major commercial rigid and flexible solar cells and modules is provided, evaluating their structural, electrical, and mission-performance characteristics, with a focus on integration into lightweight solar arrays for planetary science missions in harsh space environments. First, the fabrication of high-specific-power arrays is examined in detail, considering both reliable commercial products and emerging technologies, covering solar cells, photovoltaic assemblies, protective layers, and substrate arrays. This is followed by the discussion regarding the design constraints related to interconnections and the construction of lightweight wing architectures, including their evaluation under Earth gravity. Afterward, the next section focuses on current flight heritage across various orbital and interplanetary missions, including LEO, GEO, Mars rovers, and asteroid probes, with attention to performance trade-offs and power delivery metrics. Ultimately, we evaluate the role of flexible solar arrays in upcoming missions involving stratospheric platforms, lunar habitats, Mars expeditions, and Venus atmospheric exploration. This review underscores the critical role of flexible photovoltaics in enabling scalable, power-efficient architectures for next-generation space systems.

SUMMARY

Flexible and lightweight solar arrays are crucial for advancing space missions by offering high specific power, compact stowage, and reliable deployment in various space environments. This review explores the development of flexible photovoltaic technologies, examining the evolution of solar cells, modules, and arrays, with a focus on their application in planetary science missions and orbital services. It details the fabrication of high-specific-power arrays, including commercial products and emerging technologies, and discusses the challenges in designing lightweight architectures and interconnections. The review also assesses the photovoltaic performance of these arrays in orbital and interplanetary missions, highlighting the trade-offs in power delivery and radiation hardness. The findings emphasize the role of flexible solar arrays in enabling scalable, power-efficient systems for upcoming missions, including lunar habitats, Mars and Venus exploration. This work underscores the importance of flexible and deployable photovoltaic technologies in shaping the future of space exploration and services, supporting next-generation space systems.

KEYWORDS

Specific power, solar cell assembly, photovoltaic assembly, flexible substrate, lightweight solar cell, flexible interconnection, folded array, roll-out architecture, radiation hardness.

INTRODUCTION

In 1958, just four years after the first commercial solar cell was introduced by Bell Laboratories, a 1 W solar array consisting of six single-crystal silicon solar clusters (**Figure 1A**) marked a significant milestone in the use of solar energy for space applications. This solar array powered the small, spherical Vanguard 1 satellite, which was made of aluminum, weighed 1.46 kg,¹ and measured 16.5 cm in diameter, with a specific power of less than 0.68 W/kg.² Vanguard 1 demonstrated the critical importance of solar cells in the space industry, providing a long-lasting power source for spacecraft operating at a reasonable distance from the Sun. From the modest milliwatts on the Vanguard 1 satellite to multiple kilowatts on the International Space Station (ISS), having the largest solar arrays in space (**Figure 1B and C**), solar cells have been a fundamental power source for nearly every satellite, becoming indispensable for military operations, scientific research and communication. The pathway to achieving the current state-of-the-practice (SOP) solar arrays has been enabled not only by advancements in efficient solar cell technology but also by innovations in deployment systems for large architectures, particularly compact and lightweight designs that maximize the available power per payload in space. For instance, specific power, expressed as power-to-mass or power-to-volume ratio, has become a crucial parameter and a key technological requirement for science missions such as space exploration.³ Achieving an optimal balance between the mass and volume of solar cell arrays, the energy supply for equipment and thrusters, and the operational range is critical. To address these challenges, various photovoltaic assembly (PVA) architectures have been developed, including deployable systems with both rigid and flexible solar panels or blankets designed to form larger “wings”.⁴ In particular, flexible substrates have driven the development of high-specific power systems that integrate rigid or semi-flexible, highly efficient multijunction (MJ) solar cells (with efficiencies exceeding 30%). One example is the UltraFlex™ array design, which demonstrates that the beginning of life (BOL) specific power values greater than 150 W/kg can be achieved under standard radiation condition (AM0, ~1365 W/m²) and 60°C.⁵

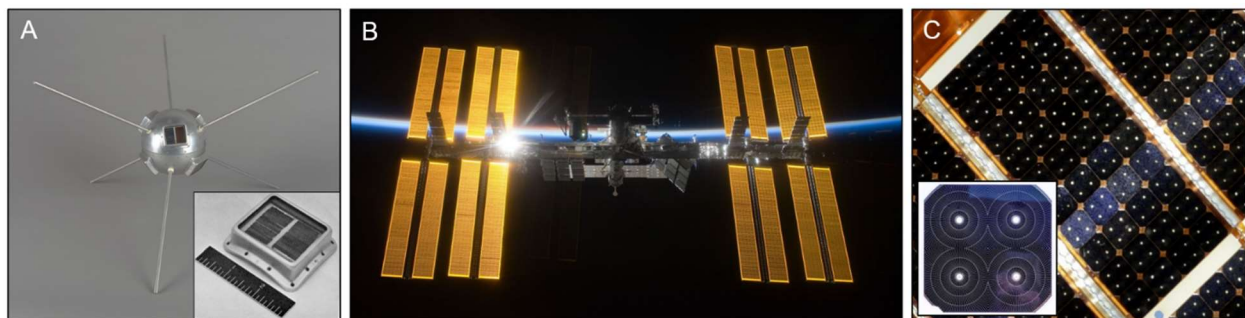


Figure 1. Benchmarks of solar cells and arrays in space.

(A) Replica of Vanguard 1 at the National Air and Space Museum, Washington, USA. *Credit/Copyright: National Air and Space Museum.* The inset shows one of the original solar clusters used in this small satellite. *Credit/Copyright: UCSB Experimental Cosmology Group.*

(B) First generation of the deployable ISS solar arrays as seen from Space Shuttle Discovery on March 25, 2009. *Credit/Copyright: NASA.*

(C) ISS constituent flexible solar cell blankets (first generation). *Credit/Copyright: European Space Agency (ESA).* The inset shows their constituent silicon solar cell (80x80x0.062 mm), fabricated by SPECTROLAB (K6700B Wrapthru Version 2) with a specific power approximately of 368 W/kg.⁶ *Credit/Copyright: Museum of Solar Energy (MOSE).*

Since one of the earliest proofs of concept for a PVA using silicon solar cells in the 1960s⁷, only a limited number of studies and patents have been published by 2000 (**Figure 2a**). Many of these innovations were

classified under space agencies and military defense programs in countries like the United States and the former Soviet Union, remaining secret until recent decades. Additionally, it is undeniable that nuclear power sources have significantly influenced the planning of space missions, as they have proven to be a reliable and solar-independent power option for deep space exploration.^{8,9} This confidentiality and use of nuclear systems explains the relatively low track of development of space technologies like flexible solar cell architectures in public/academic conferences and scientific articles (**Figure 2A**). This scenario has changed over the past years, with clear trends emerging in the development of commercial radiation-hardened flexible devices. These advancements focus mainly on flexible and thinner silicon solar cells and arrays^{10,11}, lightweight III-V MJ solar cells and coupons^{12,13}, flexible cover glasses and protective layers^{14–16} and thin film devices as copper indium gallium selenium (CIGS), hybrid perovskite and organic solar cells.^{17–23} These research trends are evident in the co-occurrence analysis of keywords from scientific articles over the past decade, as shown in **Figure 2B**.

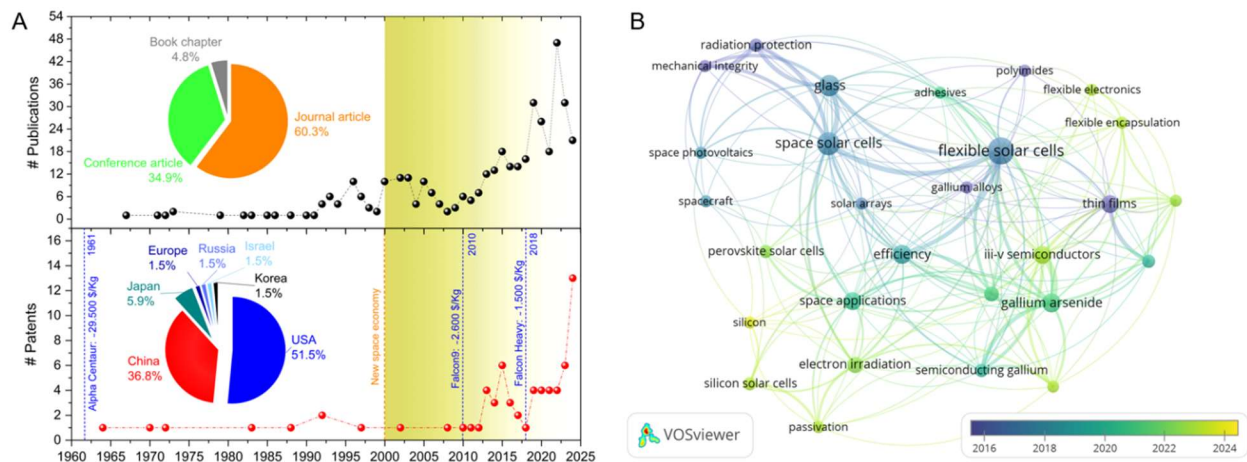


Figure 2. Timeline of the most relevant disclosed and protected information about flexible and lightweight PVAs for space applications based on findings in Web of Science and Scopus databases.

(A) Scientific publications and public patents by April 2025. The dates listed for the patents correspond to when they were granted. On average, there is a 4-year gap between the filing of the application and its approval.

(B) Co-occurrence network of keywords based on conferences, book chapters, scientific reviews and journal articles related to flexible and lightweight modules and arrays for space applications. This diagram is obtained from a refined research including 201 publication records. This diagram visually illustrates the interconnections between keywords to show how they appear together within abstracts, titles, publication keywords, and highlights in a collection of scientific publications in a period. In this diagram, each keyword is represented as a node, and a link (or edge) connects two nodes if those keywords frequently occur together in the same context, such as within the same sentence, paragraph, or document. The strength or thickness of the links reflects how often the keywords co-occur.

There is no doubt that the 21st century came up with a space industry more accessible and open to new markets. The new space economy is a rapidly evolving landscape of commercial activities in outer space. Unlike traditional space exploration dominated by governments, this new era is driven by private companies aiming to profit from space-based activities. It encompasses a wide range of sectors, including satellite communications, Earth observation, space tourism, asteroid mining, and even colonization efforts. Innovations in technology, reduced launch costs from the Alpha Centaur to the Falcons rockets have fueled this boom, making space more accessible and economically viable than ever before. The emergence of the new space economy has fostered interdisciplinary collaboration and strengthened confidence between the public and private sectors, while introducing new actors beyond the United States and Russia (**Figure 2A**). China has become a key player, demonstrating its advanced technological capabilities in lunar exploration and telecommunications, besides, building its own space station. For instance, Chinese patents now account for approximately 63% of all published patents related to the development of flexible PVAs in the 2020-2024 period, a significant increase from the 4% during the 2010s when the United States dominated patent applications (**Table 1**). Throughout this decade, the fabrication and deployment in Low Earth Orbit

(LEO) of the first generation of solar arrays on the ISS marked a pivotal moment in the development of flexible and deployable solar cell wings in space. These arrays, also known as “Legacy arrays” or Solar Array Wings (SAWs), were launched and installed between 2000 and 2009. Each SAW consists of two retractable blankets (**Figure 3A**) of silicon solar cells (~14% BOL efficiency at AM0) with a mast between them (**Figure 3B**), which is 35 meters long and 12 meters wide, providing approximately 28 W/kg at 1 AU (31 kW and 1080 Kg)^{24,25} (**Figure 3C**). Considering the technological limitations, solar cell efficiency and mission costs at that time, this specific power is still remarkable compared with the largest solar wings ever installed on a spacecraft as for 2024. These photovoltaic arrays on the Europa Clipper and JUICE spacecraft, both targeting the Jovian system, feature highly efficient III-V MJ solar cells (>28% BOL efficiency at AM0) arranged in two deployable wings, will have an average specific power output of 1.27 W/kg and 2.18 W/kg at approximately 5AU, respectively.²⁶ It is important to highlight that these values appear to be quite low compared to other SOP deployable solar arrays in Earth orbits. Since these wings were designed for low irradiance and low temperature (LILT) conditions around Jupiter and their moons, if they were used on a spacecraft in LEO, power densities of 30-40 W/kg and 54-75 W/kg could be expected for Europa Clipper and JUICE, respectively. From this correlation, eight Europa Clipper solar arrays could be fabricated using the ISS SAWs. This comparison clearly highlights the large size of the ISS and its substantial energy demands, which have been met by the Legacy arrays and batteries. However, over the past decades, these arrays have suffered degradation due to the harsh space environment. Studies conducted during the initial years of operation estimated an average output decay of 0.3% per year for the short-circuit current.²⁷ This decrease in performance has been attributed to a combination of environmental stressors affecting the solar arrays, including radiation damage from high-energy electrons and protons, optical degradation and surface contamination caused by ultraviolet (UV) radiation, atomic oxygen, and thruster plume byproducts, as well as plasma-induced sputtering and arcing, impacts from micrometeoroids and orbital debris, and the mechanical fatigue resulting from repeated thermal cycling. To address the potential energy shortfall on the ISS, between 2021 and 2023, the largest rollable flexible solar cells arrays ever made were installed and deployed along the central part of the SAWs up to two thirds of their length. A total of eight Roll-Out Solar Arrays (ROSAs), featuring an unique deployable architecture using composite booms, were attached to the ISS (iROSA), demonstrating the capabilities of high specific power, flexible and rollable solar arrays for future missions and commercial space applications (**Figure 3D**). Developed by REDWIRE (formerly Deployable Space Systems - DSS)^{28,29}, each iROSA unit, comprising a pair of flexible blanket arrays, measures approximately 20 meters in length and 6 meters in width, which corresponds to about half the length and width of a full deployed ISS SAW (**Figure 3E** and **Figure 3F**).^{30,31} According to data provided by REDWIRE, this lightweight flexible blanket has the potential to deliver a specific power exceeding 100 W/kg, with a nominal output greater than 20 kW. This remarkable power density, achieved through the use of upright lattice-matched MJ solar cells (30.7% efficient XTJ Prime solar cells developed by Boeing's SPECTROLAB), flexible substrate and composite lightweight booms, is further reflected in its potential stowed volume capacity exceeding 40 kW/m³, which is about forty times greater than the legacy ISS foldable SAWs.³² ROSA paved the way for new applications in space exploration of flexible arrays, as seen in the successful Double Asteroid Redirection Test (DART) mission³³, in the commercial market with telecommunications satellites like Ovation 3³⁴, and in the near future to power the first segment of NASA's lunar Gateway.³⁵ Apart from the flexible blanket in the ROSA architecture and circular wing design in spacecrafts like Lucy (referred sometimes as UltraFlex™), highly efficient III-V MJ solar cells have contributed significantly to the success of these array technologies. The heritage of space solar cells is extensive, with a long-standing dominance of these devices due to their outstanding efficiency, radiation resistance, and flight-proven reliability. The III-V MJ solar cells have powered a wide range of missions, from Earth-orbiting satellites to deep space exploration. Recent advancements in materials science and manufacturing techniques are driving a new wave of innovation toward thinner, lighter, and more efficient photovoltaic solar cells. These next-generation space devices are designed not only to enhance performance but also to enable lower-cost processing and higher-throughput production methods, addressing key economic and logistical constraints.³⁶ Within this evolving landscape, flexible silicon, CIGS, perovskite and organic solar cells are emerging as promising candidates to reshape solar array architectures, particularly for LEO applications.³⁷⁻⁴⁴ Their potential to be manufactured using scalable

techniques such as roll-to-roll and sheet-to-sheet, combined with the inherent mechanical flexibility of their substrates, positions them as attractive alternatives to traditional rigid panels. Moreover, their compatibility with lightweight deployment systems and reduced launch mass offers a complementary solution to the conventional III-V MJ technologies. As research continues to improve their stability and radiation tolerance, these new materials are poised to play an important role in the future of space technologies. Meanwhile, III-V MJ solar cells are also evolving towards higher efficiency and flexible designs, targeting high production and lower fabrication costs to maintain their key position in the upcoming space ecosystem.

Table 1. List of public patents related to flexible solar modules and arrays for space applications. The arrow indicates the transition between companies that changed their name or were absorbed by larger corporations. Patent records as of April 2025.

Patent	Title	Grant	Year	Country
US3459391A	Interconnection of solar cells	National Aeronautics and Space Administration, NASA	1964	USA
US3544041A	Deployable flexible solar array	Communications Satellite Corp	1970	USA
US3658596A	Flexible solar cell modular assembly	Lockheed Missiles Space	1972	USA
JPS58168280	Manufacture of solar battery array for space	Tokyo Shibaura Denki KK → Toshiba	1983	JAPAN
US4755231A	Flexible solar array cell and substrate therefor	Trw Inc.	1988	USA
JPH04146897	Flexible solar battery array	NEC Corporation	1992	JAPAN
US5296044A	Lightweight stowable and deployable solar cell array	Northrop Grumman Innovation Systems LLC	1992	USA
US9214892B2	Solar arrays	Northrop Grumman Systems Corporation	1997	USA
US6402881	Process for electrically interconnecting electrodes	University of California	2002	USA
US20080173349	Solar cells for stratospheric and outer space use	United Solar Ovonic LLC	2008	USA
JP2010166010	Converging closed space three-dimensional solar cell	Watanabe Tsutomu	2010	JAPAN
US8061660B2	Large-scale deployable solar array	Composite Technology Development, Inc.	2011	USA
US8356774	Polyimide substrate bonded to other substrate	US Air Force	2013	USA
US9620658B1	Integrated modular photovoltaic blanket assembly for space solar array	Deployable Space Systems Inc → Redwire Space	2013	USA
US8387921B2	Self-deploying solar array	Composite Technology Development, Inc.	2013	USA
US8376282B2	Collapsible structures	Composite Technology Development, Inc.	2013	USA
US8872018	Atomic oxygen and electrostatic-resistant, flexible structure for space applications	Boeing Corporation	2014	USA
US8683755B1	Directionally controlled elastically deployable roll-out solar array	Deployable Space Systems Inc → Redwire Space	2014	USA
US8232129B2	Method for bonding solar cells directly to polyimide	Boeing Corporation	2014	USA
US9105782	Arrays of ultrathin silicon solar microcells	University of Illinois	2015	USA
US8974899	Pseudomorphic glass for space solar cells	US Air Force	2015	USA
US8993366B2	High efficiency, lightweight, flexible solar sheets	MicroLink Devices Inc	2015	USA
CN105207577A	Flexible solar cell array based on shape memory polymer composite material and expansion method of flexible solar cell array	Harbin Institute of Technology	2015	China

US9758260B2	Low volume micro satellite with flexible winded panels expandable after launch	Effective Space Solutions R&d Ltd → Astroscale Israel Ltd	2015	Israel
CN204452956U	The semiclosed split type manned lunar rover vehicle	Shanghai Aerospace System Engineering Institute	2015	China
US20170033247A1	Flexible antenna integrated with an array of solar cells	University of Michigan	2016	USA
US9450131	Rollable and accordion foldable refractive concentrator space solar array panel	Deployable Space Systems Inc → Redwire Space	2016	USA
US20160137319A1	Method for releasing a deployable boom	Solaero Technologies Corp → Rocket Lab	2016	USA
US20170012154A1	Method for producing solar cells and solar cell assemblies	Solaero Technologies Corp → Rocket Lab	2017	USA
US9676501B1	Space solar array architecture for ultra-high power applications - ROSA	Deployable Space Systems Inc → Redwire Space	2017	USA
US2018000617	Flexible conducting cover glass replacement for satellite solar panels	New Mexico Tech Research Foundation	2018	USA
US10340843	Solar panel with flexible optical elements	Airbus Defence and Space Netherlands B.V	2019	EU
US10189582	Elastically deployable panel structure solar array	Deployable Space Systems Inc → Redwire Space	2019	USA
US10276736B1	Flexible solar array	Solaero Technologies Corp → Rocket Lab	2019	USA
US10381499B1	Flexible solar array and method for fabricating the same	Solaero Technologies Corp → Rocket Lab	2019	USA
US10530294	Ultra-thin, flexible and radiation-tolerant eclipse photovoltaics	United States Secretary of the Navy	2020	USA
US20200202404	Automated assembly and mounting of solar cells on space panels	Solaero Technologies Corp → Rocket Lab	2020	USA
RU2735449C1	Binary space with reconfigurable antenna combined with a rollable solar battery, deployable multivector matrix rocket engines	Ryazan State Radio Engineering University	2020	Russia
CN110901958A	Lightweight foldable large-scale flexible solar cell array supporting structure	Shanghai Institute of Satellite Engineering	2020	China
CN109686815B	Manufacturing method for positioning and upper plate pasting of flexible array solar cell module for space	Shanghai Institute of Space Power Sources	2021	China
CN113793880A	Full flexible self-folding solar array	Shanghai Institute of Space Power Sources	2021	China
JP2021082819A	Flexible solar array	Jiangsu Yixing Derong Technology Co Ltd	2021	China
US20210091247	Interconnection of solar cell modules	Solaero Technologies Corp → Rocket Lab	2021	USA
US20220037541A1	Flexible solar array for extraterrestrial deployment	Northrop Grumman Systems Corporation	2022	USA
CN114050195A	Flexible CIC battery and preparation method and application thereof	Beijing Borui Atomic Space Energy Technology Co Ltd	2022	China
CN114373816A	Solar array and preparation method and application thereof	Atomic Space Energy Technology Co Ltd	2022	China
US20220321056A1	Retractable mast solar array	Opterus Research and Development Inc	2022	USA
JP2023148193	Solar cell on which cover glass with conductive coating is stuck and mounting method thereof	Mitsubishi Electric Corp	2023	Japan
JP2023047317	Lightweight flexible solar array	Boeing Corporation	2023	China
CN116960229A	Preparation method of large-area space full-flexible solar cell array module	Harbin Institute of Technology	2023	China
US20230050780A1	Z-fold flexible blanket solar array	Maxar Space LLC	2023	USA

CN117878172A	A flexible solar cell array substrate for aerospace and a preparation method thereof	Cetc Blue Sky Technology Co Ltd	2023	China
US20230238464A1	Back contact solar cell assemblies	Solaero Technologies Corp → Rocket Lab	2023	USA
US11962272B2	Z-fold solar array with curved substrate panels	Maxar Space Llc	2024	USA
CN117878172A	Flexible solar cell array substrate for spaceflight and preparation method thereof	Cetc Blue Sky Technology Co Ltd	2024	China
CN115832089B	Space flexible solar cell array and packaging method and application thereof	Suzhou Fuchang Space Technology Co Ltd	2024	China
CN119018370A	Satellite reel-type flexible solar wing deployment and retraction device	Shanghai Engineering Center for Microsatellites	2024	China
CN119677214A	Flexible solar cell array converging production process method and flexible solar cell array	Shanghai Gesi Aerospace Technology Co Ltd	2024	China
CN118879075A	A method for preparing a solar cell flexible packaging composite material	Harbin Institute of Technology Shenzhen	2024	China
CN118888620A	A fully flexible solar cell array suitable for low temperature and low light intensity environments	Harbin Institute of Technology Shenzhen	2024	China
CN118545265A	A rope-driven flexible solar wing deployment mechanism	Shenyang Institute of Automation of CAS	2024	China
CN118645543A	A thin-film gallium arsenide solar cell module for spacecraft	Shanghai Juanzhe Technology Co Ltd	2024	China
CN118637437A	A winding flexible solar cell array deployment and retraction mechanism and method	Northwestern Polytechnical University	2024	China
CN118867018A	Flexible thin-film solar cell array interconnection structure for extreme temperature environments in space	Cetc Blue Sky Technology Co Ltd	2024	China
CN117713660B	Dual-mode variable structure space folding and unfolding solar cell array system	Shenzhen Institute of Northwestern Polytechnical University	2024	China
CN117937674A	Flexible photovoltaic energy storage control integrated power supply device	Yangtze River Delta Solar Photovoltaic Technology Innovation Center	2024	China
CN119551220A	Flexible solar wing	Shanghai Gesi Aerospace Technology Co Ltd	2025	China
CN119403239A	Solar cell array for spacecraft and preparation method and application thereof	Suzhou Fuchang Space Technology Co Ltd	2025	China

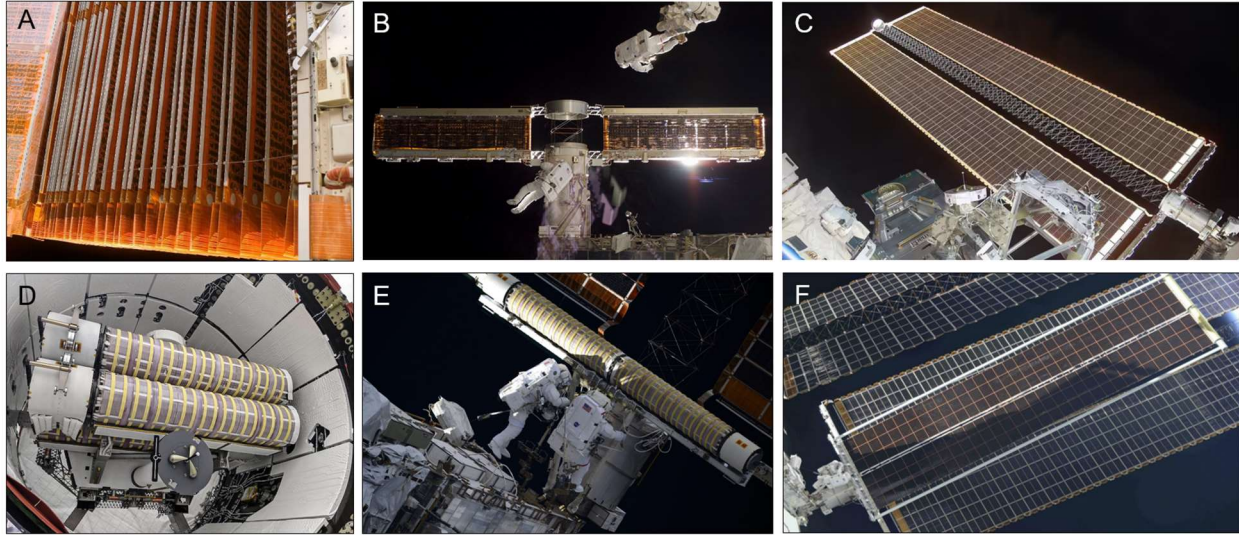


Figure 3. Solar cell arrays on the International Space Station

(A) Folded first ISS Legacy array (P6–Port), featuring silicon-based solar cell blankets during the STS-116 Shuttle Mission (2006). *Credit/Copyright: NASA*

(B) Compact Telescopic Array (CTA) with a pair of stowed/retracted Legacy blankets (P6–Port), prior to installation on P5 (Port) during the STS-116 mission (Expedition 14 crew). *Credit/Copyright: NASA*

(C) Fully deployed Legacy array viewed from inside the Space Shuttle Endeavour (2002). *Credit/Copyright: NASA*

(D) Two iROSA units stowed inside the Dragon cargo capsule before launch in 2021 (SpaceX CRS-22 mission). *Credit/ Copyright: SpaceX/REDWIRE*

(E) Stowed iROSA unit at the far end of the port-side truss, prior to deployment on an existing Legacy array (Expedition 65 crew, 2021). *Credit/ Copyright: Boeing*

(F) Second iROSA unit (reddish in appearance) fully deployed at a 10-degree angle relative to the ISS's existing solar panels (2021). *Credit/ Copyright: REDWIRE*

DESIGN OF LIGHTWEIGHT AND FLEXIBLE SOLAR CELL ARRAY ARCHITECTURES

Solar cell arrays for space applications can be broadly categorized into two main categories: body-mounted and deployable arrays, with further subdivisions based on their structural and substrate configurations (Figure 4). Deployable blankets or wings play a crucial role in the development of flexible solar array architectures, utilizing lightweight, rollable or foldable substrates such as polyimide, glass-, carbon-, and epoxy-based composites.^{45–47} In addition to their reduced mass, these substrates offer significant advantages, including compact stowage within a cargo capsule prior to deployment in space, lowering launch costs. Furthermore, they can provide essential protection for their constituent solar cells during pre-validation tests on Earth and before landing on extraterrestrial surfaces such as comets, planets, and moons (landers, rovers, space probes, for instance). These advantages are clear when it is only considered the standalone substrate and solar cells. A holistic array design is a trade-off between these components and complementary materials, electronics and equipment needed to build the deployable wing. While the specific power (W/kg) remains a key figure of merit in spacecraft power system design, it is important to consider that in large deployable solar arrays, the mass contribution of passive components, such as cover glass, protective layers, interconnectors, booms, and deployment mechanisms, can significantly reduce the impact of lightweight photovoltaic materials on the overall system-level performance. As a result, the benefit of high specific power at the cell or substrate level may be partially offset when integrated into complex deployment structures. Therefore, a comprehensive evaluation should consider both specific power and the total system mass and volume to accurately assess the performance of large-scale space solar arrays. For that reason, designing a flexible solar array is a complex process that must be adapted to the specific requirements of each space mission. However, there are some standardized procedures or similarities that can be found in different patents for building the solar cell array up to the wing level (Table 1). In these cases, the process begins with a bare solar cell, to which cover glass, bypass diodes, and interconnectors are added to form the solar cell assembly (SCA). Some companies refer to this device as cell-interconnect

cover glass (CIG) assembly. The SCAs are then connected in series to form strings, which are typically combined in parallel to build the photovoltaic assembly (PVA). In many lightweight PVAs, particularly those based on roll-out or flexible blanket architectures, the active solar layer is supported by a flexible substrate that often incorporates a printed interconnect circuit underneath. To ensure a robust design that protects the flexible PVA, a sandwich-like architecture can be implemented, in which the PVA is encapsulated with transparent films such as polyimide or silicone. This configuration is one possible approach and does not represent a universal design, as other flexible array architectures may omit encapsulation or adopt alternative protective strategies. Finally, the number of PVAs, or the individual panels or modules that comprise them, used to construct a wing depends on the mission's power requirements (energy output and duration) and the specific spacecraft design. Alternative PVAs designs and material configurations are discussed further in the manuscript.

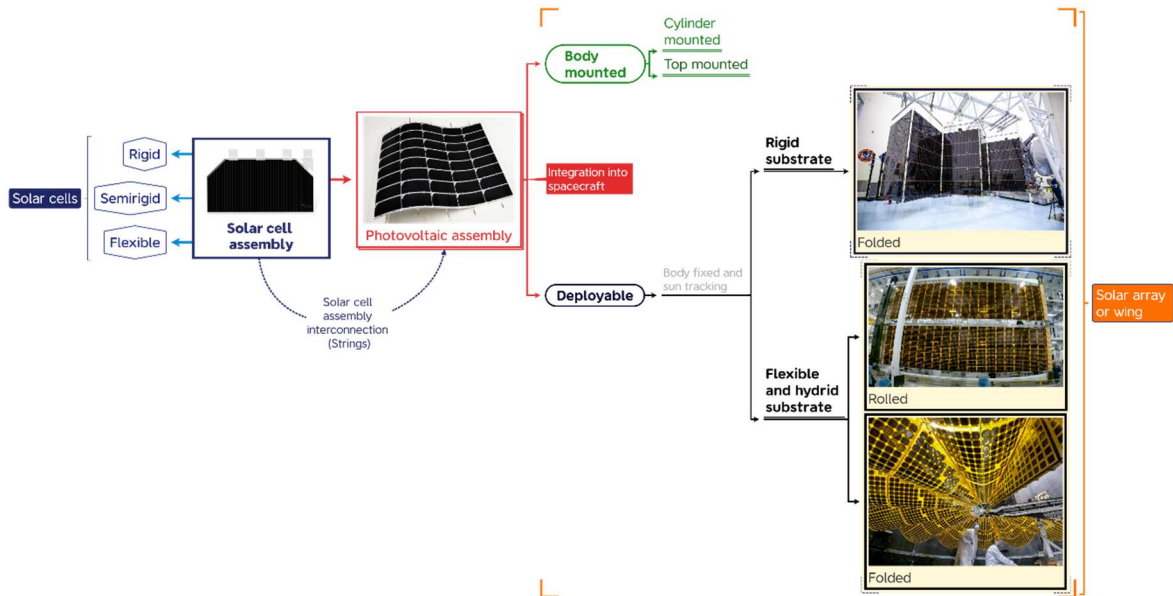


Figure 4. Diagram of photovoltaic array families used in space applications based on their integration in a spacecraft, substrate nature and stowage system.

The left part highlights that both rolled and folded flexible solar arrays can be fabricated using any type of solar cell and are not limited to flexible devices. The substrate primarily determines the flexible nature of the photovoltaic assembly. This diagram is adapted from Ashford et al.⁴⁸ Solar cell assembly: 32% Efficiency Triple Junction GaAs Solar Cell Assembly Type: ES-32TJSC-30: *Credit/Copyright: Suzhou Everlight Space Technology Co., Ltd.* Photovoltaic assembly: Lightweight, flexible solar module with a conversion efficiency of 32.65%: *Credit/ Copyright:SHARP.* Rigid substrate (Folded): Europa Clipper Solar Array Alignment, Installation and Integration (2024): *Credit/Copyright:NASA/Kim Shiflett.* Flexible and hybrid substrate (Rolled): Deployment of 60 kW ROSA for the lunar Gateway's Power and Propulsion Element (PPE) (2025): *Credit/ Copyright:REDWIRE.* Flexible and hybrid substrate (Folded): NASA's Lucy spacecraft solar arrays (2021): *Credit/Copyright: Lockheed Martin.*

Traditional rigid and flexible solar cells for space applications

During the 1980s, silicon solar cells were the primary power source for spacecrafts, with their efficiency improving from 10% to over 14% at the end of this decade.⁴⁹ In the 1990s, GaAs solar cells began to replace the silicon devices, evolving from single-junction to dual-junction cells on germanium substrates, which were more cost-effective than GaAs.⁵⁰ By the 2000s, MJ devices, specifically triple-junction solar cells (3J) became the standard for most space missions, with further advancements leading to the development of quadruple-junction (4J) architectures in last decade^{51–53}. Today's 3J solar cells achieve BOL efficiencies greater than 28% at AM0 (~135mW/cm²) and 25°C, additionally, demonstrating enhanced resilience to the harsh conditions of space. A detailed heritage overview of commercial space solar cells up to July 2025 is provided in **Table 2**. It is important to highlight that the space market is evolving rapidly across multiple regions, with the entry of new companies supplying high-efficiency space solar cells. For

example, several Chinese manufacturers, including Enchampion Aerospace Technology Co., Ltd., China Germanium Co., Ltd., San'an Optoelectronics, Suzhou Everlight Space Technology Co., Ltd., Derong Technology Co., Ltd., and the Shanghai Institute of Space Power-Sources (SISP), offer GaAs-based solar cells with efficiencies exceeding 30% at AM0. Similarly, in Europe and South America, companies such as O.C.E. Technology (Ireland), CAVU Aerospace (United Kingdom), and the Ecuadorian Space Agency (EXA) are contributing to the growing pool of suppliers. This scenario reflects a broader diversification of the supply chain, strengthening global access to advanced photovoltaic technologies for space applications.

Table 2. Heritage of commercial space solar cells. Physical quality: Flexible refers to a commercial device that uses a flexible substrate or cover layer, and with a bending radius greater than 2 cm. Photovoltaic values are associated at AM0 (135-137 mW/cm²) and 23-28°C evaluation condition. Data are based on publicly available sources like datasheets and NASA reports ⁵⁴. The Rocket Lab's III-V 5J solar cell with 34% BOL (IMM-β) is not referenced in this table, as it is under qualification according to the roadmap company.⁵⁵

Company, country	Solar cell name	Technology	Physical quality	Thickness (μm) ^a	Size (cm ²)	V _{oc} (V)	J _{sc} (mA/cm ²)	BOL Efficiency (%)	Pmax ^b (W/m ²)
AZUR Space, Germany	Silicon S 32	Silicon	Rigid	130	23.61	0.62	45.80	16.9	229.2
	3G30C-Adv	III-V 3J	Rigid	150	26.51	2.70	17.20	29.5	403.0
	3G30C-Adv ^c	III-V 3J	Semirigid	80	30.18	2.70	17.23	29.5	403.0
	4G32C-Adv	III-V 4J	Semirigid	110	30.18	3.45	15.20	31.8	434.7
	TJ 3G28C	III-V 3J	Rigid	150	30.18	2.66	16.77	28.0	382.5
CESI, Italy	CTJ-LC	III-V 3J	Rigid	80-150	68.60	2.62	17.30	28.3	387.0
	CTJ-30	III-V 3J	Rigid	150	68.60	2.60	17.80	29.1	398.0
	CTJ30-Thin	III-V 3J	Semirigid	80	26-30	2.61	17.80	29.0	396.0
Rocket LabSolAero ^d , USA	ZTJ	III-V 3J	Rigid	--	--	2.72	17.40	29.5	397.7
	ZTJ+	III-V 3J	Rigid	--	--	2.69	17.10	29.4	397.9
	ZTJ-Ω	III-V 3J	Semirigid	70-100	--	2.73	17.40	30.2	408.2
	Z4J	III-V 4J	Rigid	--	--	3.95	12.00	30.0	407.1
	Z4J+	III-V 4J	Semirigid	--	--	3.72	13.4	31.3	423.7
	IMMα	III-V >3J	Semirigid	50-150	--	4.78	10.70	32.0	433.1
	ZTJM	III-V 3J	Rigid	--	--	2.63	17.76	29.5	392.7
SPECTROLA B (A Boeing Company), USA	XTJ	III-V 3J	Rigid	140-500	26-59	2.71	18.10	29.5	399.6
	XTJ-Prime	III-V 3J	Semirigid	80-225	27-84	2.75	18.60	30.7	415.9
	XTE-SF	III-V 3J	Semirigid	80-225	< 85	2.78	18.00	32.2	433.4
	XTE-HF	III-V 3J	Semirigid	80-225	27-80	2.75	18.10	32.1	433.3
	XTE-LILT	III-V 3J	Semirigid	80-225	27	2.66	17.14	31.6	427.9
	UTJ	III-V 3J	Rigid	140-500	26-59	2.52	32.00	28.4	384.9
	ITJ	III-V 3J	Rigid	140-170	< 31	2.63	17.76	26.8	363.2
EMCORE – SolAero, USA ^e	BTJM	III-V 3J	Rigid	140	26.60	2.70	17.10	28.5	386.3
	E-ZTJ	III-V 3J	Rigid	140-150	26.60	2.72	17.40	29.5	397.7
MicroLink, UK	IMM3J	III-V 3J	Flexible	< 30	20	2.97	15.00	28.5	390.0
MicroLink, US	IMM3J	III-V 3J	Flexible	< 30	20	3.04	15.93	30.4	434.0
Solestial, USA	SolGEN2	Silicon	Flexible	<30	30-140	0.74	46.00	20.0	273.7
AscentSolar, USA	Titan ^f	CIGS	Flexible	55	929	--	--	17.5	182.9
SHARP, Japan	Si-CIC	Silicon	Rigid	180-200	< 30	0.66	46.80	17.4	237.8
	Ge-3J	III-V 3J	Rigid	< 200	4-77	2.67	17.50	28.7	391.7
	IMM3J	III-V 3J	Semirigid	< 120	4-27	3.05	16.42	31.0	423.3

Yim Space, China	GaAs	III-V 3J	Semirigid	30-35	12-30	3.08	16.30	30.0	412.0
	SC-3GA-3	III-V 3J	Rigid	170-300	30	2.74	17.30	30.0	403.0

^a Average thickness when there is a single value.

^b Maximum power output per area.

^c Thin solar cell version

^d In 2021, Rocket Lab closed the acquisition of space solar power products company SolAero Holdings, Inc.

^e In late 2014, EMCORE sold its space photovoltaics business to SolAero Technologies Corp.

^f 17W module is expected to be available soon.

It is evident that the majority of commercial spacecrafts, rovers, landers and science probes utilize III-V 3J solar cells, as they have been shown to be more efficient and stable under high radiation doses and extreme temperatures compared to silicon solar cells.^{56–58} However, like other bulk crystalline solar cells, these devices are typically mechanically fragile and have limited tolerance for bending. To address these issues, research over the past decade has focused on thinning III-V MJ devices, particularly through the use of the epitaxial lift-off (ELO) process. This approach has enhanced flexibility without compromising their BOL efficiency, and in some cases, improving the radiation tolerance^{59–61}. A notable example of this advancement is the commercial AZUR Space 3J solar cell, specifically the 3G30C-Adv model, which is available in thicknesses of 150 and 80 μm (rigid and semirigid, respectively), both achieving an efficiency of 29.5% under AM0 WRC (World Radiometric Reference, 1367 W/m^2) spectrum (**Table 2**). The key distinction between these devices lies not only in their flexibility but also in their specific power. As shown in **Figure 5A**, for the 3G30C-Adv solar cell architecture, a significant performance improvement can be achieved from 454.5 W/kg to 805.9 W/kg (**Figure 5B**) on average by reducing the thickness by 70 microns in devices without cover glass, with sizes of 26.51 cm^2 and 30.18 cm^2 , respectively (**Table 2**). This performance in thinner devices can also be seen in other commercial solar cells, such as the CTJ30-Thin from CESI (80 μm , 26.5 cm^2), which has a specific power approximately of 806.7 W/kg . In the quest of higher power densities, MicroLink Devices and SHARP have achieved highly competitive values exceeding 3000 W/kg with a device thickness of about 30-50 μm (**Figure 5C**). This race for lightweight devices is not exclusive to III-V MJ solar cells. Emerging thinner silicon, CIGS, perovskite and organic solar cells are also at the forefront of a new revolution in flexible technology. Companies like Solestial (**Figure 5D**) and Ascent Solar (**Figure 5E**), specializing in silicon and CIGS PVAs respectively, have demonstrated sufficient maturity to be considered for new roll-out and folded blanket designs in future space missions. For instance, Opterus, under contract with NASA, will utilize Solestial's flexible solar cells to fabricate its lunar and patented solar array (US20220321056A1) known as Retractable Rollable Mast Array (R-ROMA)^{62,63}. In the case of perovskite solar cells, emerging devices such as those being developed by Commonwealth Scientific and Industrial Research Organisation (CSIRO) are narrowing the gap and reducing uncertainty in the use of flexible perovskite materials in space.³⁷ They have demonstrated fully printable and deployable devices (**Figure 5F**) with acceptable tolerance to proton radiation in laboratory conditions, and soon in real LEO environment.⁶⁴ With regard to organic solar cells, while this technology is mature for terrestrial applications, several organizations have actively explored its potential in space environments. In the academic sector, recently researchers at the University of Michigan have demonstrated that small-molecule organic photovoltaics (OPV) can withstand simulated space radiation, exhibiting excellent resilience to proton exposure.⁶⁵ Additionally, the OSCAR project, led by Hasselt University (Belgium) in collaboration with ESA's REXUS/BEXUS program, conducted the first successful flight demonstration of organic solar cells in the stratosphere, validating their performance under near-space conditions and reinforcing their potential for future lightweight space power systems.⁶⁶ These new players of flexible and lightweight technologies offer cost-effective processing on a large scale, making more affordable devices compared to III-V MJ solar cells for low-orbit applications although their reliability must be determined. All these advances are crucial for developing a robust and sustainable supply chain, essential for meeting the future high demand for space solar cells and arrays in telecommunications, observation constellations, and space-based power beaming systems.^{67–70} Concerning this last application, although the concept of the space energy beaming has existed for several decades and has been technically evaluated in recent years in projects such as Solaris at ESA⁷¹, it remains a topic of strategic interest due to its potential for continuous and high-efficiency energy delivery from orbit. This scenario is supported by numerous project proposals

received in the Horizon Europe call, “In-space solar energy harvesting for innovative space applications”, funded by the European Innovation Council (EIC) in 2023.⁷² This call aimed to develop technologies for in-space energy harvesting and transmission to re-translation stations or other receivers, such as Moon bases. Complementary, ongoing projects such as CASSIOPeIA (UK Space Agency) and space-based solar power (SBSP) initiatives integrated into China’s national space program (Manhattan project), highlight the continued global investment in assessing its feasibility.^{73–76} Companies like Airbus are also actively engaged in developing enabling technologies.⁷⁷ While efficiency and scalability challenges persist, these efforts demonstrate that space power beaming is regarded as a serious and potentially transformative energy strategy by both public institutions and private stakeholders. In resonance with these needs, III-V multijunction (MJ) solar cells are progressing toward higher efficiencies and lower fabrication costs, as reflected in the various architectures mainly developed through metal-organic vapor phase epitaxy (MOVPE) deposition. A comparison of the qualities of these SOP architectures and the emerging devices mentioned above is presented in **Table 3**.

Table 3. Overview of conventional and emerging solar cell architectures for space applications. The first column lists the main processing techniques associated with each photovoltaic technology. The "Architectures" column outlines the key characteristics of each device type, including MJ architecture, layers composition and companies or organizations linked to each solar cell. The device configuration only highlights the main absorber materials and semiconductors, which are disclosed in open access datasheets and scientific articles. The arrow indicates the side of the device where the solar cell absorbs incident irradiation, specifically through the high-band gap absorber in the case of multijunction (MJ) devices. Two arrows pointing in opposite directions represent the capability of bifacial silicon solar cells to absorb light from both sides. Emerging technologies: This table includes only devices and commercial entities or research institutions that have demonstrated sufficient technological maturity to be considered near market entry.

Technology, processing	Architectures	Qualities	Disadvantages
III-V MJ, ^{78–80} MOVPE, sometimes referred as MOCVD (Metal-organic chemical vapor deposition)	<u>Lattice matched (LM)</u> →InGaP/(In)GaAs/Ge (3J): CESI, Rocket Lab, AZUR SPACE, SPECTROLAB	- Mature, well-understood technology. - Proven spaceflight heritage - High reliability	- The Ge substrate adds weight, compromising high specific power values. - Limited flexibility - Efficiency constrained by lattice-matching.
	<u>Inverted metamorphic (IMM)</u> →InGaP/GaAs/InGaAs (3J): Rocket Lab-SolAero, MicroLink, SHARP →InGaP/GaAs/GaInAs/InGaAs (4J): Rocket Lab	- Potential higher efficiencies above 33% BOL. - High specific power - Lightweight due to substrate removal by ELO process. - Potential integration in flexible array designs. - Better current matching than LM. - Reduced cost if the substrates can be used several times using ELO.	- Complex fabrication process. Long production time. - Substrate removal required. - Limited handling for very thin devices (<50µm).
	<u>Upright metamorphic (UMM)</u> →AlInGaP/AlInGaAs/InGaAs/Ge (4J): AZUR Space	- Potential higher efficiencies above 31% BOL. - Compatible with existing LM fabrication processes. - Proven better hard radiation compared to LM devices.	- Requires high-quality buffer layers. - Strain management challenges. - Expensive and slow processing.
Emerging technologies			
Silicon, ^{81,82} PECVD (Plasma-enhanced chemical vapor deposition)	<u>Heterojunction (HTJ)</u> →a-Si:H(n)/a-Si:H(i)/c-Si(p)/ Si:H(i)/ Si:H(p)← Solestial	- Enhanced radiation hardness than bulk silicon solar cells. - Suitable for thin, lightweight substrates. - Self-healing solar cell. - Cost effective devices. - High flexible solar assembly.	- Lower efficiencies compared to III-V technologies. - Low reliability for deep space applications.

CIGS,^{83,84} <i>Thermal evaporation, electrochemical and ion-beam deposition, nanoparticle printing</i>	<u>Monolithic-Single p-n junction</u> → ZnO/CdS/CIGS/Mo AscentSolar	- High compatibility with flexible substrates. - Low processing temperatures. - High flexibility, better suited to micrometeoroid damage or vibration. - Potential high specific power.	- Lower efficiencies compared to III-V and silicon technologies. - Less proven reliability compared to Si or III-V devices. - Needs robust encapsulation for space.
Hybrid perovskite,^{18,19,37,85} <i>Roll-to-Roll and blade coating, inkjet printing, thermal evaporation, pulsed laser deposition</i>	<u>Monolithic-Single p-i-n junction</u> → PEDOT:PSS/ $CS_{0.05}FA_{0.81}MA_{0.14}Pb_{2.55}Br_{0.45}/PCBM/PEIE$ → PEDOT:PSS/BA₂MA₃Pb₄I₁₃/PCBM/PEIE CSIRO	- Low production cost. - Low processing temperatures - Different options of processing. - High compatibility with flexible substrates. - Potential large production scale. - High specific power and potential hard radiation architecture. - High integration in tandem devices with other technologies.	- Less mature technology for space applications. - Very sensitive material under different ambient stressors. - Robust encapsulation is needed to ensure its reliability in space.

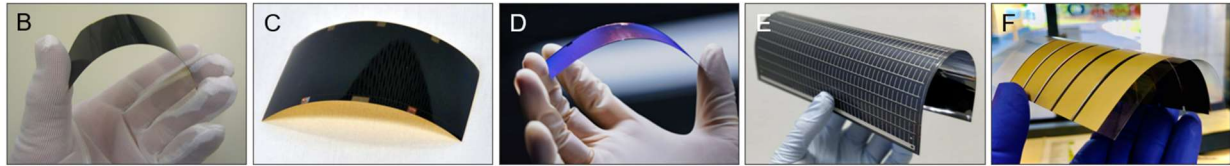
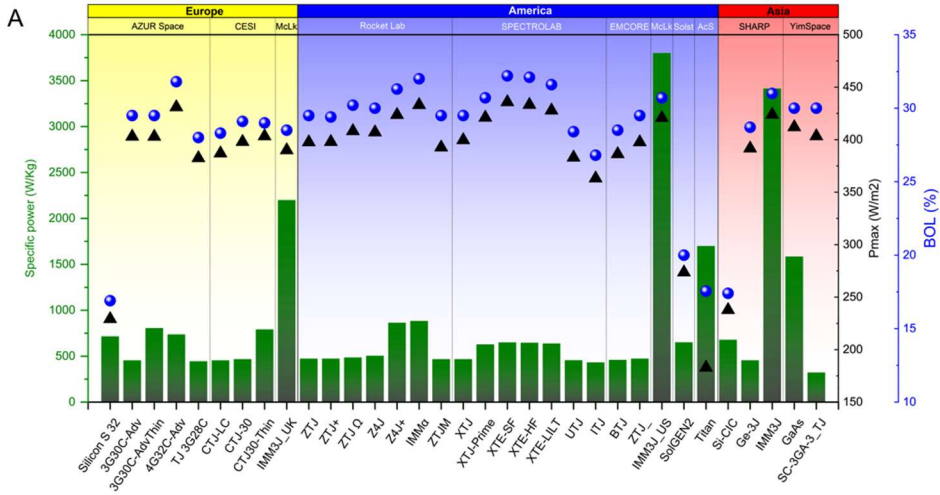


Figure 5. Commercial and emerging space solar cells.

(A) Comparative performance of the main commercial devices. The specific power values were estimated from publicly available data at AM0 (135-137 mW/cm²) and 23-28°C. Rocket Lab (SolAero): Considering a device with 49 mg/cm² average mass for semirigid devices (IMMα and Z4J+) and 84 mg/cm² for rigid solar cells. SPECTROLAB: Devices with an average cell mass of 67 g/cm². Si-CIC (SHARP): Considering a device with 35 mg/cm² average mass. The IMM-β cell from Rocket Lab is not included in the plot due to insufficient public performance data.

(B) AZUR 3G30C-Adv 3J solar cell (thin version). *Credit/ Copyright:ESA*

(C) MicroLink III-V device. *Credit/ Copyright:MicroLink Devices UK Ltd*

(D) Silicon-based Solestial solar cell. *Credit/ Copyright:Solestial*

(E) Ascent Solar CIGS minimodule (Titan). *Credit/ Copyright: The German Aerospace Center (DLR).*

(F) CSIRO printable thin film perovskite minimodule. *Credit/ Copyright: Luke Sutherland/CSIRO*

Space solar cells must be resilient to the harsh environments of space, which vary based on mission/service duration and distance from Earth. Protons, electrons, and heavy ions are considered the primary sources of accelerated degradation in their constituent layers. Consequently, any space solar array requires either specialized shielding or radiation-hardened solar cells to ensure a reliable power supply for spacecraft and its instruments throughout their operational lifetime. Since 2000, with the advent of highly efficient space solar cells, such as SPECTROLAB's and AZUR's first SOP devices^{13,86}, there has been a growing emphasis on optimizing radiation-resistant devices. Depending on the target radiation environment, several Earth-based testing methods use fluence, particle type, and energy as key parameters to assess and correlate degradation in space. For example, the European Cooperation for Space Standard (ECSS), in its latest version ECSS-E-ST-20-08C (Photovoltaic assemblies and components), specifies that, at a minimum, irradiation experiments should be conducted using two different electron energies and two different proton energies.⁸⁷ The recommended energy ranges are 700 keV to 5 MeV for protons and 1 MeV to 10 MeV for electrons. In practical applications, often constrained by the availability of irradiation facilities, electron and proton energies typically fall within the 1 to 3 MeV range for both particle types. After conducting the respective irradiation experiments and determining the beginning-of-life (BOL) and end-of-life (EOL) electrical performance of the solar cells, further analyses must be performed to obtain the characteristic degradation curves, the relative damage coefficients, and the electron-to-proton conversion factors in both Jet Propulsion Lab (JPL) and Naval Research Lab (NRL) modelling worlds.⁸⁸ Within this wide range of possible radiation conditions, a commonly adopted benchmark for radiation hardness testing has been an electron fluence of $1 \times 10^{15} \text{ e}^-/\text{cm}^2$ at 1 MeV, representing typical exposure conditions encountered over a 10–15 year mission lifespan, particularly in geostationary (GEO) orbits. As shown in **Figure 6**, the primary commercial multijunction space solar cells relied exclusively on architectures with Ge substrates and did not exceed an EOL efficiency of 27% under this standard testing by 2015. However, the introduction of metamorphic buffers⁸⁹, back-surface reflectors (Bragg reflectors)^{90–93}, ELO processing and device configurations exceeding three junctions, complemented by the inverted and upright metamorphic multijunction (IMM and UMM) solar cell design, have paved the way indirectly for reliable radiation-hardened space solar technology over the past decade.^{94,95} Simultaneously, this evolution has also led to the development of high specific-power solar cells.⁹⁶ Among the commercial devices, SHARP's solar cell stands out with its remarkable 3200 W/kg specific power and 26% EOL efficiency, making it a promising candidate for the development of lightweight solar arrays suited for deep-space missions in the near future. In this context, MicroLink's MJ device could also emerge as a key player. However, no irradiation test results are currently available for their technology, as their focus has primarily been on Earth-based applications, particularly for unmanned aerial vehicles (UAVs).⁹⁷ Apart from III-V MJ devices, Solestial's silicon solar cell has gained significant attention in the scientific community. Despite its relatively low efficiency (20% BOL and 18.7% EOL) compared to more mature technologies, this device exhibits self-healing capability after exposure to high-energy protons and electrons.⁹⁸ Additionally, its low cell mass (420 g/m²) and temperature coefficient degradation makes it attractive for small spacecrafts in LEO at altitudes below 1000 km, where stability, high power density and costs and can be more critical than efficiency. It is important to note that recent advancements in emerging photovoltaic technologies, particularly perovskite solar cells, have highlighted the need for updated radiation testing protocols that differ from the standard procedures typically applied to silicon and III-V solar cells. Traditional testing methods may not adequately capture the radiation resilience or failure thresholds of perovskite materials.⁹⁹ Due to their unique material composition, defect tolerance, and degradation mechanisms, perovskites can exhibit different responses to high-energy particle exposure. Similarly, at present, there are no standards that explicitly define flexibility requirements for space solar cells. Existing bending tests, such as those proposed in the AIAA (American Institute of Aeronautics and Astronautics) S-111A-2014 Standard (Qualification and Quality Requirements for Space Solar Cells), are more related to rigid solar cells and quantify the minimum bending radius until fracture.¹⁰⁰ However, this standard is outside the scope of determining fatigue through bending cycles, for example. Therefore, dedicated test protocols are required to ensure accurate evaluation, robustness, and long-term reliability of emerging flexible devices.

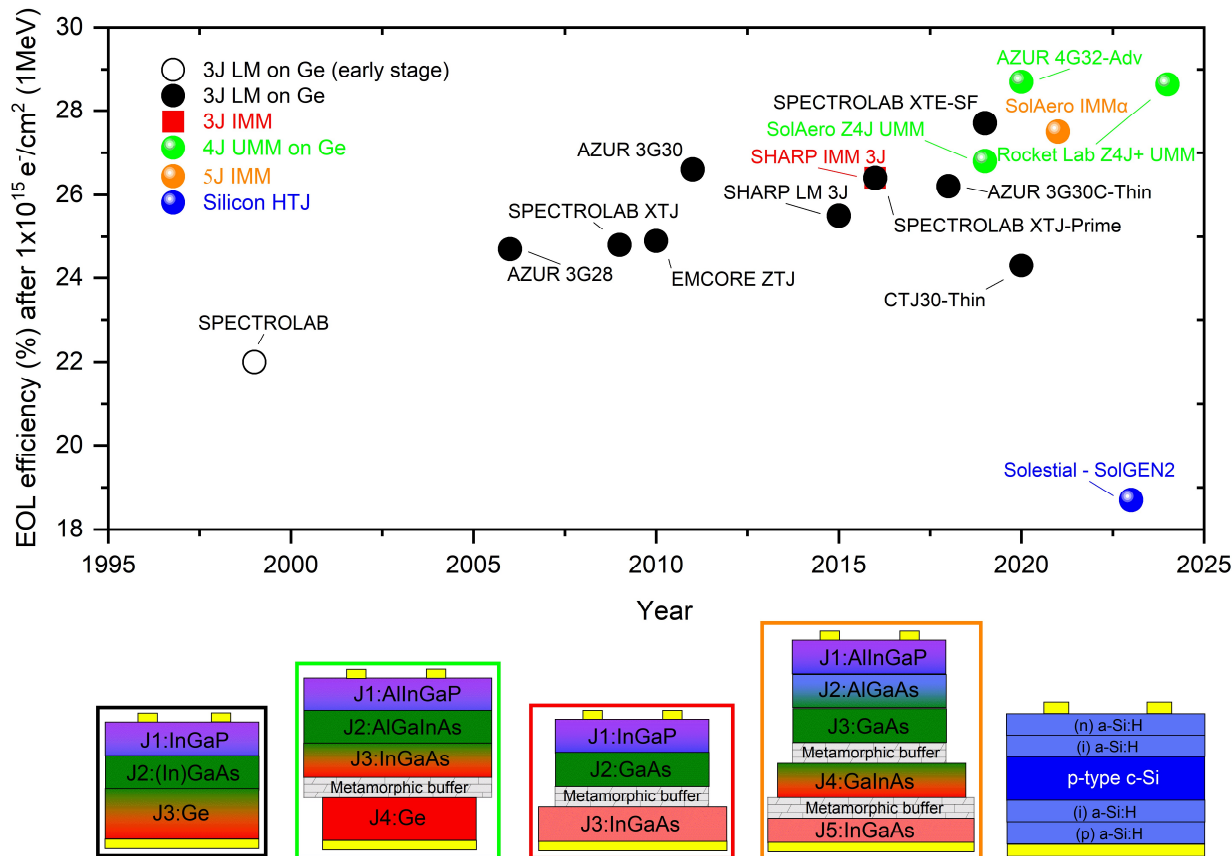


Figure 6. Timeline and device architectures of main commercial radiation-hardened space solar cells. Data and illustrations based on publicly available data (datasheets, magazine articles and brochures). The plot and architectures designs are inspired and adapted from Stevenson R. The EOL efficiency at AM0 ($135\text{--}137 \text{ mW}/\text{cm}^2$) and $23\text{--}28^\circ\text{C}$. The device architecture related to SolAero's or Rocket Lab's devices are not publicly disclosed, but a plausible architecture is suggested based on published research articles. In the first device stack, illustrated within the black square, the second junction may be denoted as either InGaAs or GaAs. Given the very low indium content in this layer, both notations are employed in literature and industry. For instance, AZUR SPACE typically designates this junction as GaAs in its solar cell products, whereas CESI adopts the InGaAs nomenclature. SolGEN2's EOL value is reported after 8 hours of annealing at 80°C under orbital sun-like irradiation. Rocket Lab's Z4J+ EOL is reported according to the ECSS-E-ST-20-08C Rev.1 post-radiation annealing procedure. The bottom architectures provide a basic illustration highlighting the main constituent layers of each solar cell. The yellow rectangle represents the top (fingers) and bottom electric contacts. The metamorphic buffer layers, depicted as gray rectangles, are essential in III-V solar cell fabrication because they enable the growth of high-quality semiconductor layers with different lattice constants. By gradually transitioning the lattice structure between the substrate and the active layers, these buffers reduce defects caused by lattice mismatch. This allows for greater flexibility in material selection and bandgap engineering, which is key to optimizing solar absorption and improving the efficiency of multi-junction solar cells fabricated by MOVPE.

Solar cell assembly

Apart from mission power requirements, the selection of solar cells and substrates for a flexible array depends on budget and spacecraft design constraints. While relying on high specific power solar cells is crucial, ultimately, the key factor is the overall specific power of the complete assembly, including substrates and all integrated components. In addition, cost and adaptability to the desired array shape are significant factors in determining solar cell size. Generally, larger solar cells ($>50 \text{ cm}^2$ or 10 cm in length) help to reduce assembly costs and minimize the risk of damage from thermal expansion in space environments with extreme temperature variations. In contrast, smaller cells, typically 2 to 4 cm wide, are recommended to prevent excessive electric load on grid lines and strings, which can sometimes cause damage due to the generation of localized high electric fields and ESD. However, this is just one of several mitigation

strategies, alongside interconnect optimization and material engineering approaches such as surface resistivity control and the use of materials with high dielectric strength. In practice, current manufacturing trends favor larger-area solar cells to enhance integration efficiency and reduce assembly complexity. Other than the solar cell area, thickness is a highly customizable parameter, ranging commercially from approximately 30 to 225 μm (**Table 2**). Commonly, solar cell thicknesses above 150 μm indicate that the device already includes a cover glass or protective layer. For bare devices, thicker cells (over 150 μm in the case of GaAs-based architectures, including metal contacts) are generally more resilient to mechanical and thermal stressors than thinner devices. However, as mentioned earlier, they have low specific power, and their robustness does not offer a clear advantage in terms of radiation stability compared to thin cells ($< 80 \mu\text{m}$). Independent of thickness, any bare solar cell exposed to high doses of high-energy particles is likely to experience a reduction in efficiency and hence specific power. As shown in **Figure 7A**, for the main commercial bare, lightweight and high efficient photovoltaic devices (excluding MicroLink solar cells), the specific power drops by approximately 13–16% for SHARP, SolAero, SPECTROLAB and CESI cells from their BOL value when they are exposed to a $1 \times 10^{15} \text{ e}^-/\text{cm}^2$ dose at 1 MeV energy. Notably, solar cells from AZUR, Rocket Lab (Z4J+) and Solestial exhibited remarkable radiation hardness, losing only 8–11% of their performance after irradiation. Clearly, they are strong candidates for future flexible solar arrays in LEO and GEO missions for service periods of up to 10 years. However, the intrinsic radiation hardness of the referred devices is insufficient to withstand the combined effects of temperature and corpuscular radiation doses from cosmic radiation, solar protons or ions, atomic oxygen (AO), interplanetary plasma and geomagnetically trapped radiation in outer space. In such cases, cover glasses become essential to ensure the required EOL power, depending on design criteria and mission time. In addition to providing radiation protection, cover glass should serve as a complementary material to help reduce the overall emissivity of the SCA. Reflective layers in the ultraviolet (UV) and infrared (IR) spectra are essential for preventing temperature rise while also protecting other constituent materials of the SCA, such as adhesives. **Table 4** outlines a representative architecture of space cover glass incorporating these materials, often referred to as UV and IR rejection layers (UVR and IRR). These layers are typically fabricated using controlled growth techniques such as thermal evaporation, physical and chemical vapor deposition (PVD and CVD, respectively), and magnetron sputtering. However, this is not the case for the adhesive material between the cover glass and the solar cell. This component is usually applied as a viscous liquid, sometimes by mixing two components, as in the case of the DW93-500 adhesive. This commercial thixotropic silicone-elastomer material, referred to as DOWSIL™ 93-500 or DOW CORNING® 93-500, is a standard adhesive that has proven high reliability in space, as it is highly resistant to a wide range of temperatures and mechanical stress in vacuum ¹⁰⁷. Furthermore, it is chemically compatible with most solar array components, making it easy to use in different solar wing designs.

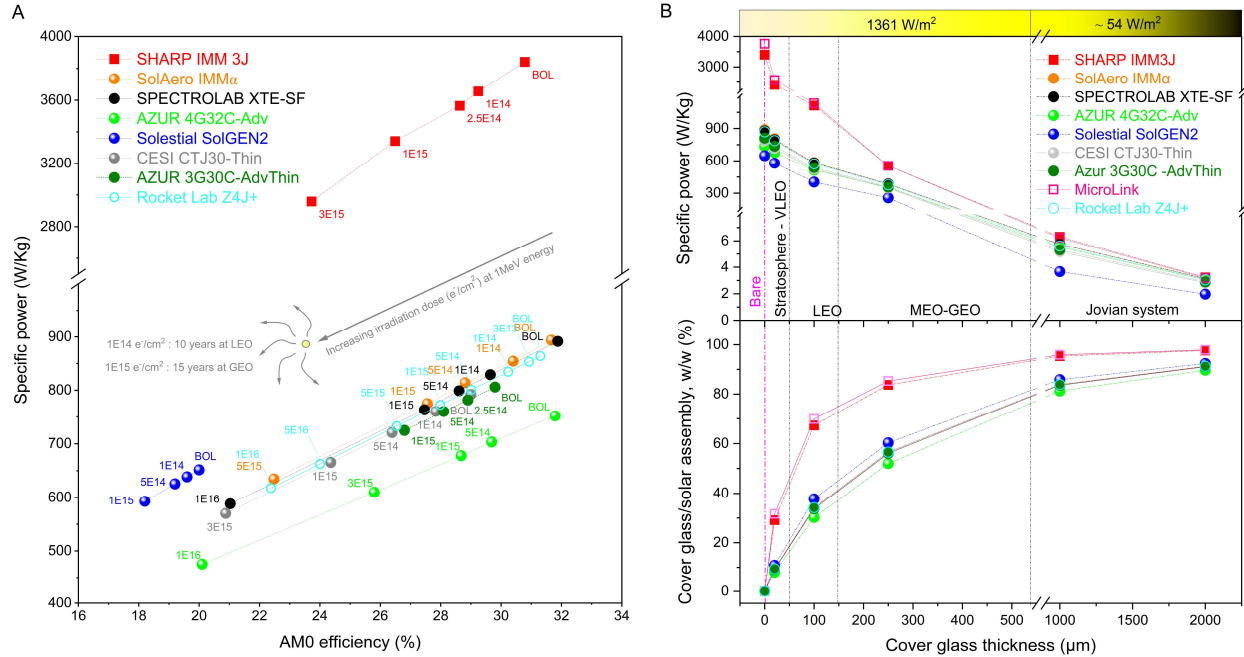


Figure 7. Potential solar cells for building flexible and lightweight space photovoltaic arrays. Data and calculations are based on publicly available sources such as datasheets and technical reports.

(A) Variation of specific power with end-of-life (EOL) efficiency at different electron irradiation doses. The representative values for the radiation hardness of Solestial's and Rocket Lab device include the healing process under light exposure at 80°C and the protocol described in the ECSS-E-ST-20-08C Rev.1 post-radiation annealing procedure, respectively.

(B) Upper: Dependence of specific power on cover glass thickness used in different environments and orbits. Bottom: Cover glass weight percentage in different assemblies (bare solar cell plus cover glass). For calculations involving the cover glass, the BOL efficiency and solar cell area of 20 cm² were used as references. Additionally, a cover glass with a 2.55 g/cm³ density, characteristic of products such as CMX, CMG, and CMO, commercialized by Qioptiq-Excelitas was considered. The following mass-per-area values (g/m²) were used for the referenced solar cells. SHARP (124), SolAero (490), SPECTROLAB (500), AZUR 4G32C (589), MicroLink (110), CESI (500), Solestial (420), AZUR 3G30C-Adv (500), Rocket Lab (490).

Table 4. Constituent layers of a standard cover glass and its bonding to the solar cell. The cover glass architecture can vary depending on manufacturer or space mission. In some cases, Layer 5 may be found after layer 3, with the adhesive directly touching the solar cell and glass.

Directly coating the solar cell and glass:			
Radiation ↓		Materials	Properties or qualities
Layer			
1	Antireflecting coating	Al ₂ O ₃ , Li-MgF ₂ /ZnS ¹⁰⁸	It helps reduce losses due to reflection, increasing the transmission of solar radiation within the absorption range of the constituent active layers.
2	Static dissipative coating	ITO, AZO ¹⁰⁸	It allows electric charge to flow to the edge of the cover glass, which is coated with metal to dissipate to ground.
3	Ultraviolet reflective/rejection (UVR) layer	Multi-layers: Al-Li-MgF ₂ alloys, SiC, B ₄ C ^{109,110}	Thermal control is achieved by blocking ultraviolet wavelengths shorter than 350 nm, which also helps to prevent adhesive degradation.
4	Glass bulk	Cerium-doped glass or fused silica ¹¹¹	Bulk radiation protection: The cerium concentration determines radiation hardness, with higher levels providing greater protection. However, this can impact glass transmission. A good trade-off is achieved at 1–2% cerium ¹¹¹ .
5	Infrared reflective/rejection (IRR) layer	Multi-layers: Ta ₂ O ₅ :SiO ₂ , TiO ₂ :SiO ₂ ^{112–115}	It is specifically used for thermal control of Ge-based multijunction solar cells by regulating IR absorption, thereby reducing the Ge subcell photocurrent.
6	Adhesive	Silicone-Elastomer DW93-500 ¹⁰⁷	Bonding material between the cover glass and solar cell, which can serve as an encapsulant and supporting material for electronics in space.
	Solar cell		

Besides its constituent layers, the thickness of the cover glass plays a crucial role in the SCA design. A thicker cover glass provides better radiation protection. For a lightweight array, a trade-off must be defined to achieve the maximum possible protection without significantly impacting the specific power and flexibility of the SCA. Depending on the mission or service requirements, the cover glass thickness can range from 50 to 150 μm in Earth orbits, with 100 μm being standard in most modern SCA assemblies in the main space agencies. For stratospheric and very low orbital applications, the cover glass can be very thin (<100 μm), with minimal impact on specific power. While thinner cover glass is standard in SPO high-specific-power arrays, thicker cover glass layers (≥ 200 μm) can play a critical role in certain Earth-orbiting future missions and services. Beyond shielding against proton radiation, increased thickness enhances durability against micrometeoroid and orbital debris impacts, as well as long-term erosion from spacecraft trusters plume, atomic oxygen and ultraviolet exposure. This added protection may be essential for extending the operational lifetime of solar cells in orbits where debris density and environmental hazards are significant, though at the expense of specific power. For example, considering a 250 μm thick cover glass for a MEO-GEO application can reduce specific power by up to 55% of the SCA, as shown in **Figure 7B** (upper plot) for highly efficient commercial solar cells. For lightest solar cells such as SHARP IMM 3J and MicroLink IMM, the reduction is even more dramatic, with specific power dropping by approximately 80% of its initial value. This effect is primarily due to the additional mass introduced to the SCA, which is directly proportional to the loss of specific power **Figure 7B**, bottom plot). Moving beyond near-Earth orbits, this photovoltaic parameter is also affected by the available energy at greater distances from the Sun, which is crucial for conducting scientific and exploration missions on comets, moons, and planets that cross the asteroid belt. For instance, in the Jovian system, where significant efforts are focused on detecting any signs of life, solar irradiance is approximately 54 W/m^2 . Based on this value and referencing cover glasses used in missions like Europa Clipper and JUICE ¹¹⁶, the specific power of the above cited cells falls below 7 W/kg (**Figure 7B**, bottom plot). This value could be improved because at such distances from the Sun, solar concentrators could be added to photovoltaic arrays to ensure a reliable power supply during the science mission. ^{117,118} It might appear that lightweight and flexible solar cells offer no advantages in deep space. However, contrary to this assumption, recent advancements in flexible and composite cover glasses have opened the door to overcoming the loss of specific power and flexibility associated with traditional protective materials in recent years. ^{15,119,120} In response, materials known as pseudomorphic glass (PMG) have emerged as a cost-effective alternative. ^{16,121} PMG consists of cover glass-like (e.g. fused silica or ceria-doped borosilicate glass) microcapsules or beads embedded in a polymeric matrix or space grade adhesive. The glass beads provide primary radiation protection, while the polymer matrix ensures mechanical integrity. These composite materials can be processed more easily than conventional cover glasses. Techniques such as spray coating and blade coating can be used to apply PMG formulations onto cells or arrays, addressing the high production costs and scalability challenges of traditional methods. Furthermore, these materials offer flexibility and additional protection for other components of the PVA or blanket, such as interconnectors and bypass diodes. They can also be processed as individual conformal sheets, which can then be used in lamination or encapsulation processes. Results regarding radiation protection have shown that PMG exhibits good tolerance to UV radiation, protons and electrons, with post-degradation performance comparable to standard rigid cover glasses. ¹⁶ In addition to their radiation shielding properties and low emissivity ¹²², PMG has the potential to mitigate electrostatic discharge (ESD) damage ¹²³, which has caused dramatic losses to spacecraft and missions over the past decades. ¹²⁴ To address ESD, researchers have proposed adding a conductive loading to the polymeric matrix or applying a thin low resistive layer to the constituent beads using materials like indium tin oxide (ITO). ¹²⁵ Besides these alternatives, the use of a conductive adhesive has also been identified as a potential option in effectively suppressing ESD. These developments in pseudomorphic glass (PMG) are well aligned with established guidelines such as MIL-STD-464C and NASA-STD-4005, which outline key strategies to preserve the electrical integrity of space hardware. ^{126,127} In accordance with these standards, the primary approaches involve the application of conductive coatings and surface treatments to minimize charge buildup, as well as the use of shielding and spacing techniques to limit coupling and discharge propagation. In addition to ensuring the electrical integrity of solar arrays, other elements must be integrated to prevent failures in cover glass-based solar cells when they are interconnected to build the PVA. Here, bypass diodes (ByD) play an important role in

protecting the strings and solar panels of potentially cascading failures. Depending on the company, solar cell technology and space mission, SCAs may incorporate a discrete (external) and monolithic integrated ByD made from silicon or GaAs, respectively (**Figure 8**). In modern space arrays, Si bypass diodes remain the baseline due to extensive flight heritage, while GaAs diodes are used in high-efficiency III–V architectures. Typically, one ByD diode per solar cell is integrated into the SCA. In the absence of these diodes, PVAs are highly susceptible to failure when a cell is partially illuminated, shaded or damaged, leading to localized hot spots and subsequent material degradation. In some cases, the SCAs have the ByD mounted on the cell back side (**Figure 8A**), which can be protected by the solar cell itself, making it less vulnerable than SCAs with a diode located in one corner (**Figure 8B**). Additional to these configurations, ByD can be grown monolithically in the solar cell. It is seamlessly integrated with one of the contacts (commonly on the n-type material) and interconnector (**Figure 8C**), facilitating its incorporation into the string assembly. AZUR and Rocket Lab offer this kind of SCA for designing special solar arrays without interconnected discrete elements.

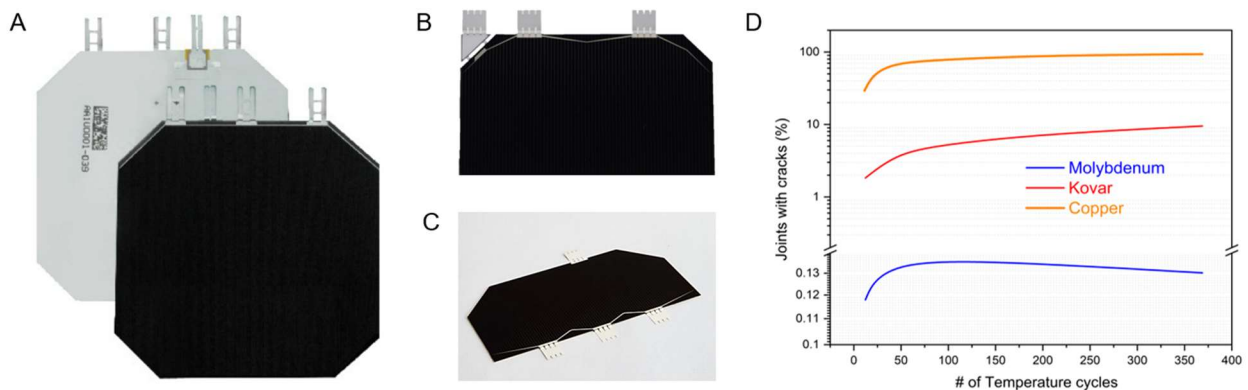


Figure 8. Solar cell assemblies and interconnector materials.

(A) XTJ SPECTROLAB SCA with a discrete bypass diode mounted on the rear side. *Credit/Copyright: SPECTROLAB*

(B) 3J AZUR space solar cell assembly (3G30A) incorporating a discrete silicon bypass diode positioned in one corner. *Credit/Copyright: AZUR SPACE*

(C) Diode monolithically integrated on the top interconnector in a 3J AZUR space solar cell assembly (3G30A). *Credit/ Copyright: AZUR SPACE*

(D) Influence of temperature cycles (75°C to -175°C) on crack formation in different interconnector materials (normalized cumulative count of cracked joints). This plot is adapted from a publicly available article by TRW Systems, which was later acquired by Northrop Grumman in 2002.¹²⁸

The design and integration of interconnectors is a crucial step in the final stages of fabricating SCAs. One of the primary reasons for performance degradation in solar arrays is the deterioration of these thin metal components (20-30µm), which can result in open strings and reduced current flow. This failure typically occurs due to crack formation at the connection interface, driven by stresses from mechanical vibrations, bending or thermal cycling. Different materials have been tested as interconnectors, with copper, molybdenum, and Kovar (an alloy of 39% nickel, 17% cobalt, and 53% iron) being the standard materials for this purpose. Under thermal stress, Kovar and molybdenum interconnectors have demonstrated better stability compared to copper due to their better thermal expansion compatibility with the solar cell and cover glass. As shown in **Figure 8D**, Kovar interconnectors show only one-tenth the failure level of those made with copper materials. Similarly, and even more remarkable, a molybdenum interconnector could have 99.8% fewer cracks compared to one made of copper.¹²⁸ This material is specifically used for magnetically clean arrays, where the spacecraft and its instruments require minimal magnetic interference to ensure accurate measurements. This is the case for current NASA and ESA missions such as Swarm¹²⁹ and Themis¹³⁰, which study Earth's magnetic field as part of their scientific objectives. Regarding copper interconnectors, they are a more cost-effective option but require clean handling conditions to prevent the formation of resistive salts caused by interactions with solder components.²⁴ Kovar interconnectors, on the other hand, are more commonly used in commercial SCAs due to their optimal cost-benefit ratio for

fabricating standard solar arrays. It is important to mention that regardless of the interconnector's base material, platinum and silver plating are commonly applied to enhance contact resistivity and solderability on the solar cell.^{131,132} In this regard, commercial SCAs generally have interconnectors embedded in both the front and rear metallic contacts of the solar cells. However, the interconnection layout can vary depending on the cell's fabrication method. For instance, ELO-based thin film flexible devices allow for interconnectors to be integrated on the same side or plane of the cell, offering potential advantages in simplifying and accelerating large-scale PVA manufacturing. This is permitted because the back metal is readily accessible from the front side of the device. In contrast, LM solar cells typically adhere to a conventional design with interconnections placed on opposite sides of the device, as illustrated in **Figure 8A**.

Photovoltaic assembly

For a flexible PVA, the chosen substrate material must not only fulfill mechanical and electrical requirements but also endure the harsh conditions of the space environment. Essential properties include high tensile strength, minimal elongation under load, electrical insulation, and resistance to thermal cycling. Additionally, the substrate should exhibit high infrared transparency to facilitate heat dissipation from the cell's back surface to space or be compatible with thermal management coatings required for the wing design. Various multilayer architectures have been explored for supporting interconnected cells, with polyimide, commonly known as Kapton™, being a widely used option.¹³³ Other composite materials, such as fluorinated ethylene propylene (FEP) combined with Teflon, FEP-impregnated fiberglass, and Mylar (BoPET, biaxially-oriented polyethylene terephthalate), have also been employed in flexible space support structures.^{134–138} The specific qualities required for the substrate depend on the space environment where the PVA will be used, but regardless of the mission or service, it is essential to match the thermal expansion coefficient of the substrate constituent layers and solar cells. This improves the thermo-mechanical stability of the solar array and prevents the need for additional insulation films in the PVA design, which could increase costs and reduce specific power. **Table 5** describes various common substrate configurations, with approximate thickness values derived from public domain handbooks and patents. While an extensive range of layer thicknesses and combinations can be used for flexible architectures, a typical design includes a printed and/or etched copper interconnect circuit enclosed or sandwiched between 25 µm thick polyimide/polyester (thermosetting adhesive) sheets. In this substrate assembly, the strings on the back contact are interconnected to the copper buses through prefabricated holes created before laminating the polyimide/polyester sheets. The bonding process that follows utilizes thermocompression or adhesive formulations containing copper-based materials or adhesives. **Figure 9A** illustrates the main steps of this fabrication process, which has been used in PVA designs by companies like Lockheed Martin for the ISS legacy solar arrays.¹³⁹ Although this approach and materials are not universally used in the space industry or suitable for all flexible array applications, it serves as a valuable introduction to the key components of the flexible assembly.

Table 5. Common substrate configuration for flexible and lightweight solar cell blankets. The layers in this architecture can be bonded by thermocompression or using special space grade adhesives or thermosetting sheets. The polymeric layers are sometimes referred to as dielectric or insulating materials, as they cannot transport electric charge in multilayer architectures.

Type	Architecture (Example)	Thickness (µm)	Qualities/Advantages
Single	Polyimide (Kapton), Polyamide (Nomex), Kevlar, Mylar, PEEK ^a , FEP-Fiberglass, Fiberglass-Epoxy (FR4), Carbon or Graphite Fibers-Epoxy.	25-125	Affordable processing for small devices. Probe of concept designs. ^{140–142}
Multilayer	Polymer/Metal/Polymer (Polyimide/Cu/ Polyimide)	50/35/25	Lightweight array for very low orbit and stratospheric applications ^{143,144} . Resilient architecture to avoid magnetic fields under high power generation. ¹⁴⁵
Multilayer	Polymer/Composite/Metal/Polymer (Polyimide/Fiberglass-Epoxy/Cu/ Polyimide)	25-40/1000-2000/35/25	Special stack for foldable wings in LEO orbit thermal cycles. ³²

Multilayer	Polymer /Polymer/Metal/ Polymer/Polymer (Polyimide/FEP/Cu/FEP/Polyimide)	25-40/17/25/17/25	Special stack for roll-out blankets in LEO- GEO orbit thermal cycles and harsh radiation. ^{146,147}
Multilayer	Polymer/Composite/Metal/Polymer (Polyimide/FEP-Fiberglass/Cu/Polyimide)	30-50/50-100/25	Special stack for roll-out blankets in GEO orbit thermal cycles and harsh radiation. ¹⁴⁸
Multilayer	Polymer/Metal/Fabric/Metal (Polyimide/Al ^b /Graphite or Mylar or fiberglass or Kevlar/Cu)	50-100/15-50/5-25/25	Special design for high radiation doses and thermal control ¹⁴⁹⁻¹⁵¹
Multilayer	Fabric/Polymer/Metal/Polymer (Mesh-membrane/Polyimide/Cu/ Polyimide)	25-100/50/35/25	Lightweight roll-out array for LEO ¹⁵²
Multilayer	TCO ^c /Polymer/Metal (ITO/Polyimide/Cu)	0.3-1/30-50/25-35	Flexible design for charge control and AO protection. ¹⁵³
Special composite	Polymer/Composite/Polymer (Polyimide/PMG/Polyimide)	25-40/120-210/25-40	Provide high specific power and flexibility to the solar array ¹⁶

^a Polyether ketone

^b Aluminum foil

^c Transparent conductive oxide

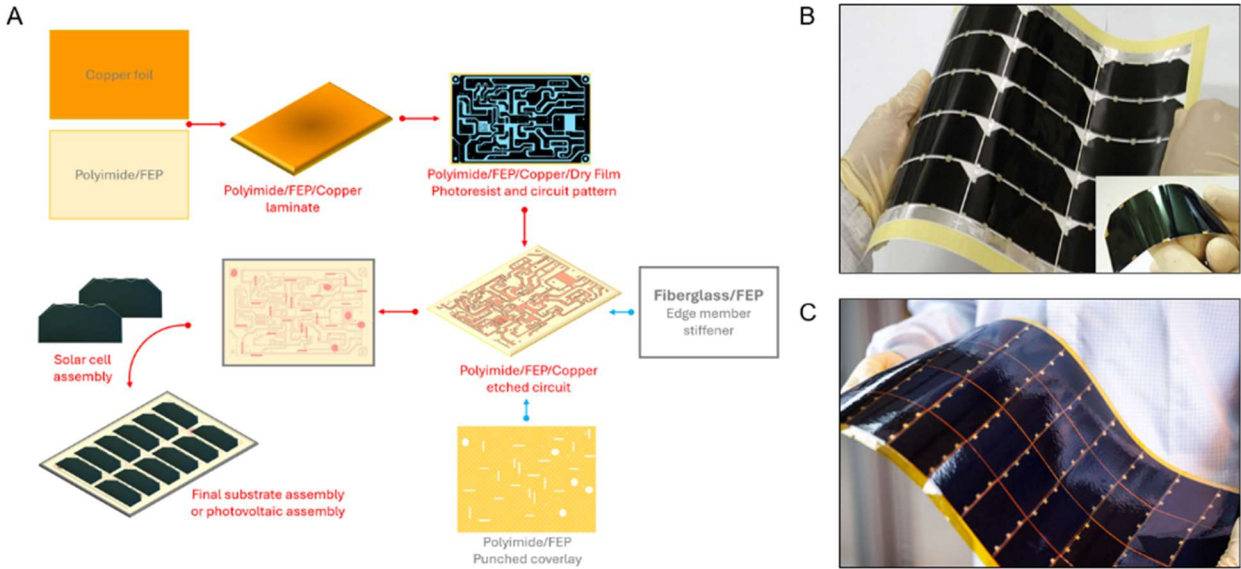


Figure 9. Photovoltaic solar cell assembly.

(A) Step-by-step process of a module assembly Kapton®FN/FEP/Cu/FEP/Kapton®HN. ¹³⁹

(B) SHARP film sheet assembly for LEO applications with IMM 3J solar cells (495.49 g/m², 590 W/Kg at BOL, 597.38 cm² and 4 cm bend radius). Credit/ Copyright: SHARP

(C) Solestial solar power module with GEN 2 bifacial silicon heterojunction solar cells. (508 g/m², 535W/Kg at BOL and 5 cm bend radius). The technical data and calculations are based on commercial product datasheets. Credit/ Copyright: Solestial.

The benefits of flexible substrates are particularly evident in their ability to support the design of large rectangular and radial PVAs while maintaining high values of power density. Companies such as SHARP and Solestial have demonstrated their expertise in producing customizable PVAs with high radiation resistance and specific power. Their lightweight mini-modules, made with IMM 3J (Figure 9b) and silicon (Figure 9c) solar cells respectively, can achieve specific power values exceeding 530 W/kg, along with a bending radius greater than 4 cm. At this level, the substrate provides sufficient rigidity to protect PVA components from excessive bending stress. However, as the size of the PVA increases, module stiffeners or additional layers become necessary to maintain structural integrity during thermal and mechanical cycling, stowage, and the vibrational forces experienced during launch. Under these stressors, the solar cell interconnects are among the most vulnerable elements of PVAs. Additionally, they must undergo voltage fluctuations based on power management requirements before and after eclipse periods. ¹⁵⁴ As

mentioned before, interconnectors or strips are mainly made from copper, Kovar, and molybdenum. However, apart from the nature and properties of these materials, their shape and design play a pivotal role in the integrity of these components.¹⁵⁵ Depending on the SCA architecture, the configuration of the interconnectors in the string design (cell-to-cell connection) differs between front-back contact and wraparound solar cells. The characteristics and properties of these interconnector arrangements are described in **Table 6**. There is no universal rule for selecting a specific interconnection for flexible solar arrays, but the Z-step and wraparound interconnector with a loop is commonly used due to its high resilience under thermal and mechanical cycles.

Table 6. Comparison of various interconnector designs to fabricate solar cells strings and arrays. ■ Interconnector. ■ n-contact. ■ Solar cell. ■ p-contact. ■ Adhesive. ■ Substrate. The size of the expansion loops mainly depends on how much and how often the gap between cells changes during the mission, and also somewhat on the shape of the substrate assembly. Other design considerations include manufacturability and potential interference of the interconnector with the solar cell coverside. In high-reliability applications, interconnector layouts may also incorporate redundant electrical paths to maintain current flow in case of localized connection failure^{156,157}.

Interconnector design		Solar cell	Qualities/ Advantages	Disadvantages
Z-Step interconnector		Front-back contact	Step deforms to provide a resilient interconnection even at low operating temperatures.	The interconnector exhibits poor fatigue life under high-low temperature cycling.
Z-Step with loop interconnector			Step and loop deform, ensuring good interconnection at low operating temperatures and providing long fatigue life.	The stress relief loop can extend above the cell surface, interfering with folded stowage components of flexible PVAs, besides posing limitations during assembly and cleaning operations.
Loop interconnector for overlapping cells			The loop deforms enhancing spin-stabilized array performance while also providing space for bypass diode. This design can maximize active solar cell active area.	A small, thick adhesive area enables high operating temperatures for oriented panels but could cause high solar cell stress, which can lead to spallation during low-temperature cycling.
Wraparound interconnector			The stress relief loops at the bottom of both cells deform in a direction perpendicular to the cell cross section. This provides resilient interconnections at low temperatures and improves fatigue life.	High interconnector manufacturing costs due to etching and relatively high assembly labor costs (handling difficulties)
"Stress-free" interconnector			Loops deform negligibly. The interconnector is not embedded in the adhesive (p-contact). This loop provides a long interconnector fatigue life and allows for inexpensive interconnection assembly.	High operating temperatures can cause interconnection damage to oriented panels.
Loop interconnector		Wraparound Contact	The loop deforms, allowing a high active cell area and, therefore, increased power output.	It is generally impractical due to interference between the solar cell cover layers and other components in folded PVAs designs. This loop can limit packing density.

In-plane expansion loop interconnector		The interconnector deforms in a plane perpendicular to the cell cross-section.	Difficulty in withstanding both in-plane and out-of-plane expansion loops simultaneously.
"Stress-free" interconnector		The interconnector deforms negligibly and is not embedded in the adhesive (p-contact). This allows for matching the interconnector and substrate coefficients of expansion through adjustments in interconnector length.	Low tolerance to torsion at the interconnector end under high temperatures.

Lessons learned from interconnectors made with expanded or photoetched silver mesh, often used for its ductility (flexibility to accommodate much of strain) and soldering characteristics, have shown that "S" shaped interconnectors are highly recommended for any SCA (**Figure 10a**).¹⁵⁷ This simple configuration helps mitigate the issue of matching the thermal expansion coefficients of PVA components and provides the necessary stress relief loops for solid interconnectors.¹⁵⁶ Additionally, these interconnectors allow easy intercell coupling to form a reliable electrical union with three degrees of freedom within the PVA (**Figure 10B**). As highlighted in , the relief loop is crucial to the lifetime of these thin components for front-back interconnection. **Figure 10C** shows that a difference of approximately 1 mm in loop height can eliminate tab failures completely under 20000 flexure cycles and extend the interconnect lifetime up to 60000 cycles. In the case of wraparound interconnectors, this difference is even more significant, with the loop providing 3.5 times longer lifetime under thermal cycle. Additionally, as an integral part of promoting this performance, the joint between the interconnector and the n- and p-contacts in two adjacent solar cells must be reliable under different space stressors. **Table 7** describes various materials and techniques that can be used for joining space hardware. Among them, soldering is the most widely used method, as it provides a strong joint that can be easily removed in case of damage or the need to replace solar cells or interconnectors in the PVA. This may occur, for example, after pre-launch array testing, such as thermal vacuum cycles or high G-level vibration tests. In contrast, joints made by welding or brazing are extremely strong but offer very little flexibility for modification or repair. Regarding joint materials, tin-lead solder alloys are commonly used due to their good thermal cycling reliability, low-temperature performance, and radiation resistance, making them well-suited for harsh space environments.¹⁵⁷ Depending on the lead content, the properties of the solder can be adjusted, as shown in **Table 8** . The lower the lead content, the better the bond strength. For more environmentally friendly options, lead-free solder alloys have demonstrated their ability to withstand extreme deep-space environments in recent years.¹⁵⁸ One such example is indium-based materials, which have shown good performance under cryogenic conditions and high particle irradiation.¹⁵⁹ On the other hand, on a larger scale, the bonding process can differ slightly from the localized techniques mentioned in Table 7. Oven soldering, where PVAs are assembled with solder in place, clamped, and then passed through an oven, can be well-suited for the rapid production of large flexible arrays. It is important to note that traditional interconnection methods such as soldering or welding, widely used in III-V and silicon-based solar cell assemblies, require elevated temperatures that can be detrimental to emerging photovoltaic materials like perovskites and organic thin films. These next-generation materials are inherently sensitive to heat and moisture, besides, exposure them to high temperatures during interconnect formation can disrupt layer crystallinity, degrade charge transport interfaces, and compromise encapsulation stability. Furthermore, recent studies have shown that soldering flux, commonly employed in standard module assembly, can chemically corrode transparent conductive oxides such as indium tin oxide (ITO), which are prevalent in heterojunction and perovskite architectures.¹⁶⁰ Such degradation leads to increased series resistance, interfacial delamination, and long-term performance loss. In light of these challenges, alternative interconnection strategies should be considered for these temperature-sensitive devices. These include thermocompression bonding, electrically conductive adhesives (e.g., films, pastes, or tapes), and low-temperature solder alloys such as indium–bismuth (In–Bi) or tin–indium (Sn–In), which

offer reduced thermal load while maintaining mechanical and electrical reliability in flexible or lightweight PV architectures.¹⁶¹

Table 7. Common techniques and materials used to join interconnectors in space hardware. While the materials described here are not universally used for all interconnectors or suitable for every flexible PVA, they provide an overview of key components that may be involved in joining these elements, depending on the space mission requirements.

Technique	Material/Alloys	Qualities/ Advantages	Disadvantages
Soldering ^{162–165} (Resistance, laser)	Sn-Ag Sn-Ag-C Pb-Ag Pb-Sn-Ag Au-Sn AgTi Ag-Pd-Ti	- Electric current is applied to generate localized heat, joining thin metal interconnects. - Low process temperature (reduces thermal stress). - Specialized high-temperature solder alloys. - Good thermal and mechanical stability. - Provides localized heat application for precision soldering, reducing thermal stress.	- Brittle joint at cryogenic temperatures. - Prone to tin whisker formation. - It can degrade under thermal cycling in space.
Welding ^{166–169} (Ultrasonic, resistance)	Sn-Ag Ti-Al-V Ti-Al-Sn Kovar Ni CuCrZr,	- High-frequency vibrations are used to create solid-state welds, commonly used for aluminum and copper interconnections - Electric current is applied to generate localized heat, joining thin metal interconnects. - Provides precise and controlled welding with minimal heat-affected zones.	- High heat input can damage sensitive components. - Some materials are difficult to weld.
Brazing ^{131,170–172}	Ag-Cu-Zn Ag-Cu Ag-Cu-P CuCrZr CuBe ₂ Au-Pd	Uses high-melting-point filler metals to join components under controlled atmospheres or vacuum.	- It requires a high processing temperature. - It can introduce thermal stress in delicate components. - Flux residues may need removal.
Wire bonding ^{173–176}	Cu, Pd-Cu Au Al-Si	Thermosonic bonding: A combination of heat, ultrasonic energy, and pressure is used to bond components.	- Limited mechanical strength. - Prone to fatigue failure under vibration and thermal cycling. - Gold-aluminum intermetallics may cause bond degradation.
Adhesive bonding ^{131,157,177} (Conductive adhesives)	Cu, Ag, Pd, Au, Ni Graphene	- Silicon- and Epoxy-based adhesives filled with conductive particles or flakes. Easy handling and application. - Pressure sensitive adhesive tapes	- Lower electrical and thermal conductivity compared to soldering/welding. - Long-term degradation under space radiation and vacuum. - Difficult to rework.

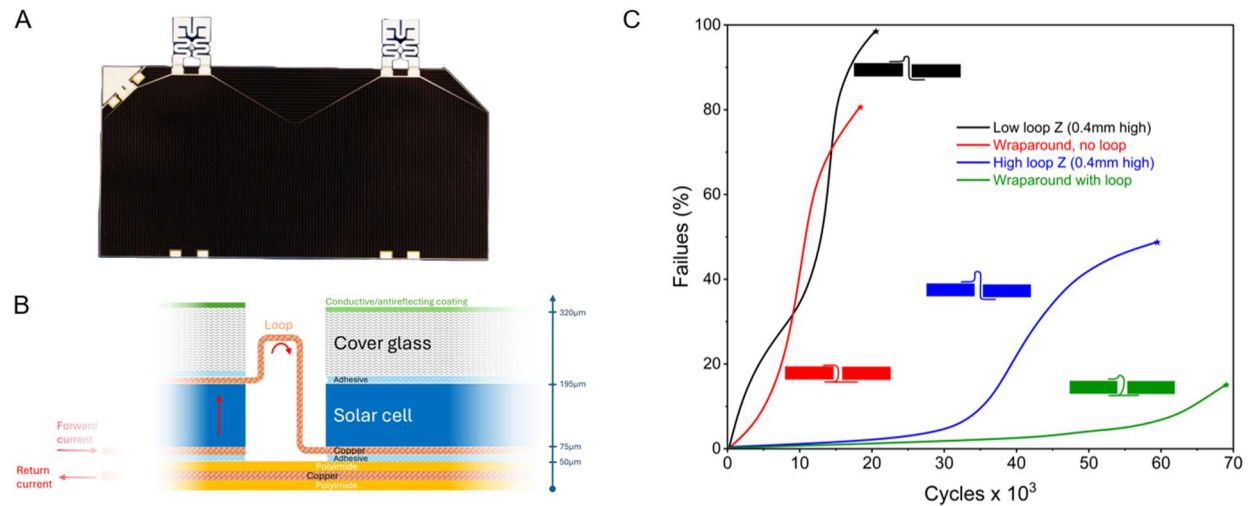


Figure 10. Interconnector configurations and qualities.

(A) “S” shape notched ribbon interconnectors commercialized by Rocket Lab (SolAero) in a SCA (IMM-α CIC). *Credit/ Copyright: Rocket Lab (SolAero)*

(B) Cross-section view of a typical interconnection (stress relief loop Z) between two CIC solar cells in a flexible substrate. The space between cells can be filled with a dielectric material.

(C) Effect of interconnection design, including stress relief loops, on failure occurrences under flexion stress cycles. This graph is adapted from a study made in silicon-based PVAs.¹⁷⁸

Table 8. Common solder compositions used for joining space electronic hardware. Adapted from a JAXA’s report.¹⁷⁹ The eutectic point elucidates the operating temperature range of any solder material, as above this temperature, it undergoes a phase transition from solid to liquid.

Solder composition	Eutectic point (°C)	Applications
Sn ₁₋₃ /Pb _{97.5-94.5} /Ag _{1.5}	309	Designed for high-temperature and cryogenic applications but has lower bond strength compared to Sn ₆₃ composition.
Sn ₆₀₋₆₂ /Pb ₃₆₋₃₄ /Ag ₂	179	Adapted to prevent the silver diffusion on ceramic substrates.
Sn ₉₄₋₉₆ /Ag ₆₋₄	221	Ideal for high-temperature environments, offering superior bond strength and excellent resistance to creep rupture compared to tin-lead solder

Apart from the above-mentioned substrate materials and interconnector design, the overall performance of a PVA also depends on the technique used to construct the solar cell strings and their bonding with the substrate. The two main assembly techniques are flat mounting and shingling, as shown in **Figure 11A**. In the shingling method, where interconnectors can be optional, the top contact of each cell is positioned beneath the bottom of the next, forming a continuous series of connected cells to achieve the desired string voltage. Rigid shingling is not commonly used for large PVAs, primarily because defective solar cells cannot be replaced easily after assembly and testing. Additionally, it has poor thermal shock characteristics. For these reasons, flat-mounted cells are preferred, as they do not overlap. This string and module fabrication requires interconnectors, permitting easier rework. Generally, the solar cells forming the rows are connected in series, and these strings are then connected in parallel to fabricate the array. Flat mounting is the most popular assembly technique, but other methods have been explored to overcome the limitations of classical shingling. A flexible shingling technique has been developed to allow close packing of solar cells in combination with the flexibility offered by interconnectors as it was described above in **Table 6**. This patented method of fabrication was used on Intelsat satellites¹⁸⁰, some of which remain operational in space. In these spacecrafts, the return electrical connection was integrated into the underside of the solar module, using either a silver mesh or a plastic foil with a printed circuit to complete the current loop.

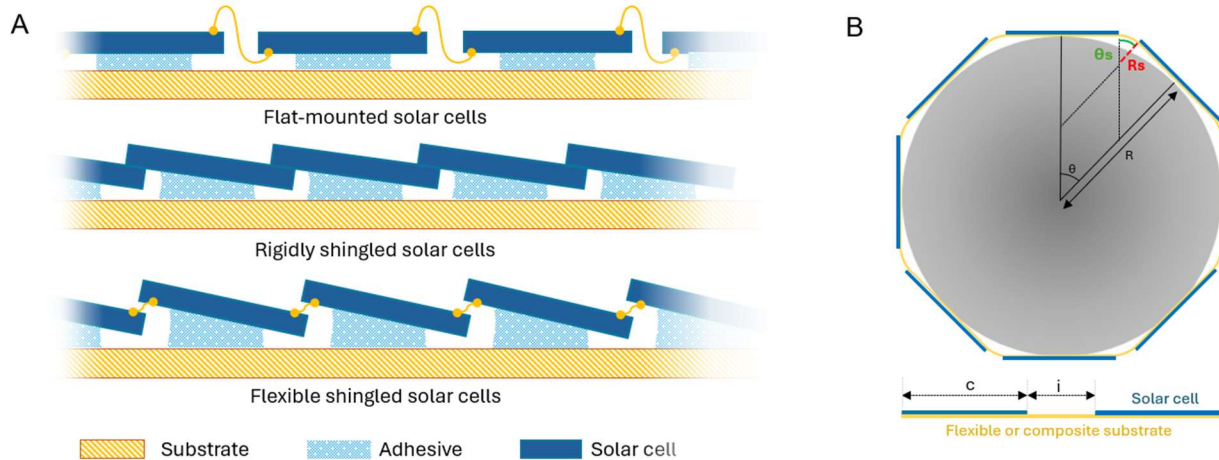


Figure 11. Examples of solar cell assembly techniques for array fabrication.

(A) Scheme portrayal of three panel construction techniques adapted from Yasui¹⁸¹.

(B) Simplified illustration of a flexible roll-out solar array. This representation is crucial as it demonstrates the feasibility of fabricating a flexible solar array using rigid or semi-rigid solar cells. The radius (R_s) and angle (θ_s) of curvature of the metal interconnect can be estimated using the following equations: $R_s = \theta_s / i \approx (i \times R) / (c + i)$ and $\theta = \theta_s \approx R / (c + i)$. The blue rectangles represent the rigid or semirigid SCAs, while the yellow line indicates the flexible substrate. This image is adapted from Jongho et al.¹⁸²

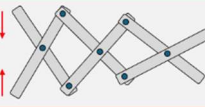
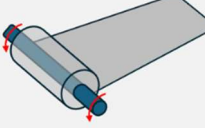
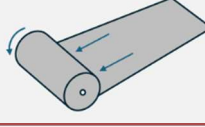
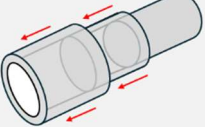
For a flexible solar cell array, it should be noted that the selection of the SCA (design and its materials) should be a holistic decision based not only on the PVA design level, but also on the wing scale. For example, in a rollable array, as shown in **Figure 11B**, its resilience under mechanical stressors, particularly during extension, retraction, and stowage, must be carefully considered. Knowing that the bending radius (R_s) and angle (θ_s) of the interconnector are critical factors in this array design, they can be determined by several elements, including the radius of the stowage cylinder (R), the size (c) and number of SCAs, and the spacing between them (i). Considering these parameters using rigid or semirigid solar cells, a flat-mounted design with flexible interconnectors or wraparound devices is more suitable than a shingling assembly. In contrast, flexible solar cells can be effectively utilized in both flat mounting and shingling methods, as they do not significantly restrict the bending of the PVA in a big array. In these setups, the properties of the adhesive at the substrate-solar cell interface play a key role in determining the array's tolerance to mechanical and thermal cycles. Similar to the fastening of the cover glass to the upper electrode of the solar cell, silicone and epoxy adhesives are commonly used to join SCAs on the PVA substrate. These materials are typically applied in thin layers (25–50 μm) and must be carefully handled due to their limited storage and pot life. Commercial products based on room-temperature vulcanizing (RTV) materials, controlled viscosity or volatility (CV), super clean or space-clean viscosity (SCV) offer high resistance to extreme temperatures, radiation, and environmental stresses. Additionally, they provide precise bonding and sealing, particularly in areas where high levels of control are required due to limited space or delicate components. Products such as DW 93500, RTV-S 691, ELASTOSIL S 692, NuSil CV-2568, and NuSil SCV-2586 are well known in the space industry for their rheological and outgassing properties, thermal stability, radiation resistance, and compatibility with the materials being bonded.^{183–188} In general, silicones adhesives are preferred over epoxy-based materials since they naturally maintain flexibility over a wide temperature range.¹⁸⁹ In some cases, adhesives require primers to strengthen the bond with the substrate. However, this is not necessary for materials like polyimides¹⁹⁰, "which offers an advantage in the design and fabrication of flexible PVAs. For these assemblies, some of the silicone adhesives mentioned above can also be used as encapsulants in the final step of their fabrication. Products like RTV566, and those from Nusil such as CV-1144, R-2188, and CV-2500, have demonstrated exceptional protection under various mission profiles, including GEO observation and planetary exploration.^{191–194} In general, these encapsulants are considered UV and AO resilient materials, optically clear formulations, as they provide protection against atomic oxygen (mainly in LEO) maintaining high transmittance in the absorption spectrum of the solar cell. Considering these qualities and cross-referencing public information (product brochures, images, datasheets), companies like Solestial could be using such materials in their PVAs. While encapsulant formulations or commercial products are not explicitly disclosed, the described features suggest the adoption of advanced strategies designed to ensure survivability in the harsh space environment, particularly given the ultra-thin and lightweight architecture of their modules.

Solar cell array

Some of the notable advantages of using a flexible PVA to build solar cell wings are related to their lighter weight per square meter. Additionally, they offer a significantly increased solar array area capability over conventional rigid honeycomb panels due to its stowage capability. Other benefits include lower fabrication costs, as they allow for the integration of wraparound solar cell technology with large scale printed circuit technology techniques, as well as the potential for fully automated solar panel production. In the building process of a deployable and flexible solar cell array, additional materials and structural elements such as hinges, dampers, wrap-around springs, booms and joints are needed to build the deployment system.^{195,196} In the case of module joints, they provide a mechanical connection between the array modules and allow their easy removal and repair. In addition, its strength must provide an adequate safety margin over design requirements. It also provides a hinge line which becomes the refold memory for array retraction. Additionally, they provide lateral stiffness, ensuring that the array strip remains flat. An example of these joints can be found in the foldable legacy modules of the ISS.^{197,198} As mentioned above, the classification of deployable solar cell arrays also depends on their stowing and extension/retraction mechanisms, as outlined in Error! Reference source not found.. Among these methods, rolled and self-extending arrays offer the advantage of reduced weight in the wing design, as they eliminate the need for electric motors and

pneumatics to unfurl the solar array in its final configuration in space.^{199,200} A notable example is the boom-assisted deployment system used in the iROSA design. In the stowed configuration, the storable tubular extendible members (STEM) booms are flattened and rolled onto a cylindrical mandrel. Using stored strain energy, the booms deploy into the extended state, utilizing eddy current dampers to control the deployment rate.²⁰¹ This system also provides sufficient stiffness to the solar array, allowing it to withstand or absorb vibrations near its natural frequency.^{202,203} In addition to the mechanical components of the flexible solar array, the substrate plays a crucial role in both electrical and thermal management. Plated-through holes and circuitry in the PVA facilitate electrical current flow between panels while also acting as thermal conduits, transferring heat from the top (cover layers and solar cells) to the bottom (flexible substrate) constituent layers. Additionally, a system of conductive pathways within each panel improves heat dissipation throughout the blanket while preserving the panel's mechanical strength under extreme temperatures. In certain cases, to improve the wing thermal management, gold-plated copper is applied to non-solar cell regions of polyimide coverlay to improve the emissivity of the PVA.^{204–206}

Table 9. Basic sketches and characteristics of stowage and extension/retraction methods of deployable solar arrays. Electric motors, mechanical springs and pneumatics can be used as prime movers for each method.

Method	Variations		Characteristics	Advantages
Folded	No joins		Stowage capability depends mainly on material stiffness and thickness. No joints are required to maintain a rigid structure.	Useful for designing inflatables arrays using composite foils to enhance stowage.
	Simple hinge join		The stow volume is approximately equal to the extended volume.	Simple design and lightweight. Preferred in heavy loaded systems.
	Multiple hinges join		It requires multiple bolts and hinge joints to ensure rigidity and minimize looseness during cyclic operation.	Very compact model and excellent deployment system
Rolled	Reel assisted		The beam is wrapped around a reel and itself, allowing one side to extend while remaining stowed compactly.	Resilient to many extensions and retractions.
	Self-extended		Self-extending design by stored spring energy. It can be partially assisted by a motor or booms.	High mechanical resistance to extensions and retraction cycles.
Telescoped	Retractable		The design provides mechanical synergy among its constituent elements to support high loads effectively. Stow capacity ranges from 20 - 50% of the extended volume.	Simple design with few parts. Highly reliable to control the array deployment and retraction.

A key challenge in developing flexible arrays is minimizing the added weight required to protect them from non-flight loading conditions. While the array operates in a microgravity environment in space, it must endure assembly, handling, testing, transportation, and storage under Earth's gravity. For these reasons, the solar cell array requires additional structural support to facilitate the necessary testing for certification prior to launch. Various deployment methods have been developed for wing testing, some of which could be adapted for flexible wings and are outlined in **Table 10**.

Table 10. Protective measures to prevent damage from nonflight loading conditions (such as gravity, atmospheric pressure, and handling forces) in deployable solar cell arrays. This is a summary of the practices used by institutions such as NASA and ESA in their lightweight solar arrays. ^{207–211}

Protective measures	Support systems	Qualities and advantages
Gravity offloading systems	Overhead suspension Systems	Use counterweights, springs, or pulley systems to partially or fully counteract gravity, simulating the weightless conditions of space.
	Air bearings & Frictionless tables	Allow arrays to move freely in a near-frictionless environment, helping test deployment mechanisms without Earth's gravitational effects.
Deployment support fixtures	Guided deployment rails	Ensure controlled unfolding of the array, preventing excessive bending or unintended stress.
	Low-force actuators	Slowly extend the array to simulate its natural deployment behavior without overstressing the structure.
Structural Bracing and Load Spreaders	Temporary stiffeners	Prevent flexing or sagging by adding structural supports during transportation and handling
	Soft clamping mechanisms	Secure delicate parts of the array without causing localized stress concentrations.
Thermal & Vacuum Testing Protection	Chamber fixtures	Secure arrays inside thermal vacuum chambers while minimizing physical constraints on their deployment.
	Protective covers	Shield delicate components from contamination, moisture, or electrostatic discharge (ESD) during testing.

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PAST AND PRESENT: HERITAGE FLEXIBLE AND HIGH SPECIFIC POWER SOLAR MODULES AND ARRAYS.

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In the early days of space exploration, spacecrafts required only a few watts of power. Today, energy demands vary significantly, with small CubeSats operating on less than ten watts, while large communications satellites and the ISS require tens or even hundreds of kilowatts. ⁵ To ensure this energy supply, solar arrays have undergone significant transformations over the decades, evolving from early heritage designs with high power and one-axis foldable configurations to modern architectures featuring complex radial deployment systems with remarkable specific power. Among these solar cell arrays, three major families have been developed and successfully flown in space, as shown in **Figure 12**. These SOP flexible arrays include the roll-out solar cell architectures, Z-folded arrays, and fan-shaped or UltraFlex™ wings, each offering unique qualities for different profile mission and power requirements. **Table 11** highlights the main differences between these designs at their BOL and AM0.

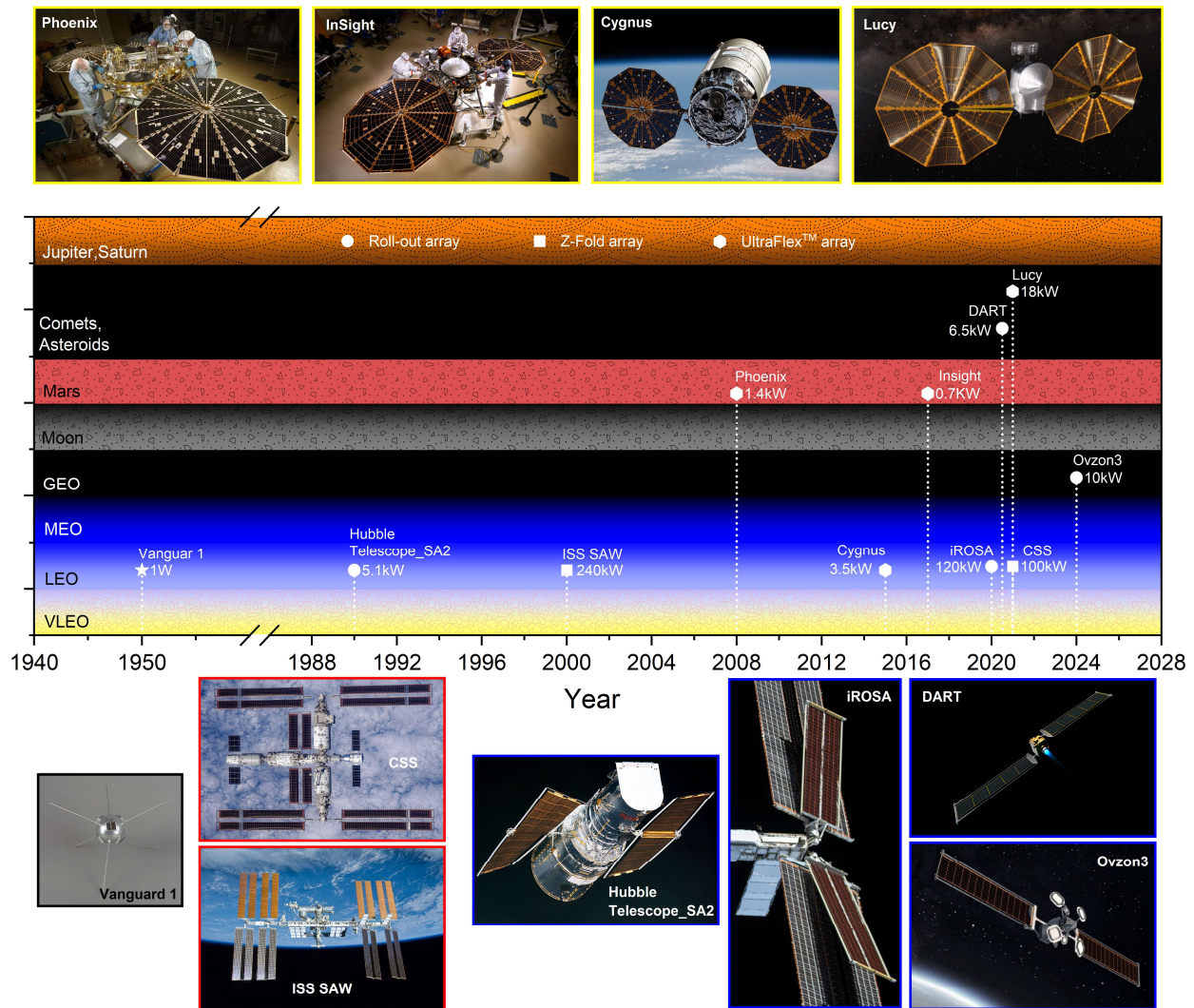


Figure 12. Timeline of the main flexible and lightweight solar arrays deployed in space and their estimated BOL power output under non-terrestrial solar irradiation ($\sim 1375 \text{ W/m}^2$). ^{212–224}

Vanguard 1 is included as a benchmark. The dates in the plot refer to the year when the arrays were deployed in space. For the ISS and CSS, they highlight the moment when the first wings were unfolded or rolled out in LEO.

Phoenix Mars lander: PIA01885: Phoenix Mars Lander in Testing (2006): *Credit/Copyright: NASA/JPL/UA/Lockheed Martin*. InSight Mars lander: PIA19664: InSight Lander in Mars-Surface Configuration (2015): *Credit/Copyright: NASA*. Cygnus: The Cygnus space cargo approaches the ISS (2022): *Credit/Copyright: NASA*. Lucy: Illustration of Lucy spacecraft solar arrays: *Credit/Copyright: NASA's Goddard Space Flight Center Conceptual Image Lab*. Vanguard 1: REPLICA of Vanguard 1: *Credit/Copyright: National Air and Space Museum*. ISS SAW: ISS seen from the departing Atlantis space shuttle, 23 May 2010: *Credit/Copyright: ESA*. CSS: The Chinese space station taken from a Shenzhou spacecraft: *Credit/Copyright: CMSA (China Manned Space Agency)*. Hubble Space Telescope_SA2: Hubble solar arrays: *Credit/Copyright: ESA*. iROSA: iROSA panels photographed during SpaceX Crew-2 fly around: *Credit/Copyright: NASA*. DART: Dart's ion thrusters: *Credit/Copyright: NASA*. Ovzon3: Illustration of Ovzon3 GEO satellite: *Credit/Copyright: Ovzon*.

Table 11. The most representative SOP flexible solar arrays in space applications. The photovoltaic performance shown here is based on BOL values for one deployable solar array or wing.

Architecture	Name	Developer	Area (m ²)	Mass (kg)	Power Output (kW)	Mass per unit area (kg/m ²)	Power per unit area (W/m ²)	Specific power (W/kg)
Z-folded	ISS SAW ²¹⁷	Boeing / SPECTROLAB	~420	~1100	~31	2.93	~45.2 – 61.2	~15.5–20.9

	CSS ^{218,225,226}	CMSA (China Manned Space Agency)	138	----	~18	---	~130.43	>40
Roll-out	iROSA ^{213,225–227}	Deployable Space Systems (DSS), (now Redwire)	119	~200	>20	~1.68	>169.5	>100
Circular	Ultraflex™ (Phoenix lander) ^{219,220}	AEC-Able Engineering (later acquired by Northrop Grumman)	6.9	62	0.25	~8.99	~36.2	~112
	MegaFlex™ ²²⁸	ATK (now Northrop Grumman)	32	~100	25	~3.13	~781.3	~250

Evolution of roll-out flexible solar arrays: From FRUSA to ROSA

Flexible roll-out solar arrays have significantly evolved over the decades, enabling higher power-to-mass ratios, improved deployment reliability, and more efficient stowage. One of the earliest roll-out solar array designs was the Flexible Roll-Up Solar Array (FRUSA) architecture, first tested in 1971 and later implemented on the Hubble Space Telescope (HST) ²²⁹, a joint project between NASA and the European Space Agency (ESA). Hubble's original two solar arrays, known as SA2, each measured 3.3 m x 12.1 m and featured 2x4 cm silicon solar cells (24000 devices approximately) rolled around a compact stowage drum. These arrays generated approximately 5.1 kW with a specific power of 18.75 W/kg per wing. ²¹² The deployment system of HST utilized bistable thin-walled strain-energy structures, enabling synchronized unfolding of both the solar panels and their support structures. However, structural challenges arose due to thermal flutter and transient disturbances, such as “thermal snap”, occurring during eclipse transitions. ²³⁰ These issues ultimately led NASA to replace the FRUSA arrays with more stable and rigid III-V solar cell wings (referred as SA3) in 1993 to better support Hubble's precision observation mission. ²³¹ Building on lessons learned from FRUSA, NASA commissioned Deployable Space Systems (DSS), currently Redwire Space, to develop the ROSA architecture, incorporating significant structural advancements. Equipped with III-V 3J solar cells membrane, ROSA arrays could potentially achieve a specific power of 218 W/kg and a power-to-volume ratio of nearly 40 kW/m². ^{152,227} Additionally, ROSA design replaced metallic tubes with composite lenticular booms, improving thermal stability, flexibility, and structural stiffness. In 2017, NASA successfully tested a 3 kW-class ROSA prototype on the ISS, confirming stable electrical performance in orbit. ²⁰⁰ Following this success, NASA requested DSS six 25 kW-class ROSA units for the ISS between 2020 and 2023. The first two iROSA units were successfully deployed at 10° inclination on the Legacy ISS arrays in June 2021 ^{213,232}, powering the 2B and 4B channels, significantly enhancing the station power capacity to around 120 kilowatts during orbital daytime. Building on the successful validation of ROSA coupled to the ISS, DSS advanced the development of small array variants ranging from 3 kW to 15 kW. These architectures have been successfully incorporated into spacecrafts, including the Double Asteroid Redirection Test (DART) mission, deployed in 2021^{214,215,233}, and the Ovzon 3 satellite ³⁴, launched in 2024. In the DART mission, ROSA technology was used for the spacecraft's primary power generation system. Given the mission's destination in the asteroid belt and its constrained launch mass, a high specific power was essential to minimize payload weight while still ensuring sufficient power. ROSA's flexible blanket and deployable boom design met these demands by delivering ~3.5 kW of power with significantly less mass and volume than rigid solar arrays. For the Ovzon-3 spacecraft, which targets geostationary orbit, ROSA enables more efficient payload accommodation by reducing the solar array's mass and launch volume, freeing up capacity for communications equipment. These roll-out architectures are highlighted with a blue rectangle and a filled-circle label in **Figure 12**. Additionally, new arrays are set to support the upcoming lunar exploration missions. ^{234,235} Specifically, within the Lunar Gateway and Artemis programs, the importance of ROSA is even more pronounced. The Gateway's Power and Propulsion Element (PPE) will rely on ROSA-derived arrays to deliver up to 60 kW of power to support human and robotic operations around the Moon. ²³⁶ The requirement for large-scale power delivery, combined with deep-space environmental resilience and the need for compact launch configurations,

makes ROSA's architecture an ideal choice. Recently in the same line of design, several Chinese research institutions have been actively developing roll-out flexible solar arrays. Everlight Space has designed a roll-out flexible solar array based on the ROSA architecture, which was successfully deployed in orbit on an experimental satellite in late 2024.²¹⁸ Additionally, the Shanghai Aerospace System Engineering institute has been developing a 150 m² roll-out flexible solar array, having successfully completed ground integration and deployment testing.²³⁷

The biggest flexible wings ever deployed: Z-folded solar arrays

Z-folded solar arrays are characterized by their flexible panels, a large supporting truss structure, and a deployment mechanism that sequentially unfolds the arrays in orbit. The compact Z-shaped folding configuration allows efficient stowage, but due to the high stiffness of the deployment mechanism, miniaturization remains a challenge, being not beneficial for building small arrays with high specific power. As a result, this design is more suitable for very large structures, such as the ISS and recently, the Chinese or Tiangong Space Station (CSS)^{224,238}. Regarding the ISS, its power supply system is equipped with eight wings (Legacy arrays), each consists of two retractable blankets of solar cells with a mast between them and spanning over 34 meters with a total surface area exceeding 400 m². These arrays utilize 8 cm x 8 cm monocrystalline silicon cells embedded in a polyimide-based substrate, providing a nominal power output of approximately 30 kW per unit and a total station capacity of around 200 kW.²¹⁷ In comparison, the CSS incorporates six large-area foldable solar arrays in two configurations, one deployed in the Mengtian and Wentian modules and the other in the Tianhe core module.²¹⁸ These arrays closely resemble those developed by Orbital ATK (now Northrop Grumman) and Mark O'Neill LLC, known as the PFC-CTA (Point-Focus Concentration Compact Telescoping Array).²³⁹ The CSS arrays utilize third-generation flexible gallium arsenide (GaAs) solar cells in a flexible substrate around 300µm, providing high power output while minimizing weight. Each CSS array expands to cover approximately 138 m² and generates 18 kW^{225,226}, contributing to a total array power capacity exceeding 100 kW. While the exact weights of the individual solar arrays are not publicly disclosed, the specific power could be over 40 W/kg. This merely estimation is based on the solar cell efficiency and flexible substrate used to build the foldable solar array. Although the ISS SAW produces a greater overall power output than the CSS arrays, the Chinese wings leverage advanced materials to reduce mass and hence improve specific power. These two SOP Z-folded arrays are referenced with a red square and a square-filled label in **Figure 12**.

Circular lightweight arrays: From planetary science to orbit cargo and asteroid missions

The circular or fan-shaped flexible solar arrays utilize a radial arrangement of reinforcing ribs that support triangular flexible solar panels. Their deployment mechanism enables a smooth transition from stowed to fully extended while maintaining high stiffness and structural integrity. One of the most notable designs in this category is the UltraFlexTM circular array, patented in 1997.²⁴⁰ Unlike traditional flexible arrays, this design consists of pie-wedge-shaped gores that are Z-folded when stowed and deployed around a central hub using a series of spars. Each array's gore size is tailored to its specific diameter.^{228,241} Originally, 3 m² wings were intended for the Mars 2001 lander²⁴², but the mission was cancelled. The UltraFlexTM arrays were later repurposed for the Phoenix Mars Lander (2008) with upgraded multi-junction solar cells.²⁴³ These circular arrays became the first flexible solar wings to be deployed beyond Earth's orbit for planetary exploration. Furthermore, this array could have generated a total of 1.47 kW near Earth, having the highest specific power of any deployable array flown to-date (112 W/kg)²¹⁹. Phoenix's 7 m² UltraFlexTM arrays (2.1 m in diameter each) were constructed using flexible Vectran mesh gores and graphite composite spars, all connected at a central hub. Once deployed, these arrays formed nearly circular decagons extending from opposite sides of the lander, providing 4.2 m² of functional surface area on Mars.²²⁰ Following its success in planetary exploration with the InSight Mars lander²²¹, which set a record by generating 4.5 kWh on its first Martian-day, the UltraFlexTM technology was further adopted for other applications, including the Cygnus cargo spacecraft^{223,244,245} and recently the Lucy asteroid probe^{222,246}. This spacecraft is equipped with high-performance flexible solar arrays that are just 10 cm thick when folded, but expand to nearly 7.3 meters in diameter when deployed (56 m² total area).²⁴⁷ Although these arrays were designed to operate as far as the Jupiter Trojan asteroids (~5 AU), each of Lucy's array can generate up to approximately 9 kW near Earth, achieving a remarkable specific power of around 116 W/kg.^{248,249} The radial arrays mentioned

above are sequentially illustrated in the upper part of **Figure 12**, each framed with a yellow square and labeled with a filled circle in the middle plot. Building on UltraFlex™ advancements, ATK introduced the MegaFlex™ solar array concept in 2014²⁵⁰, designed for higher power output and improved stowage efficiency. This version incorporates a secondary deployment mechanism, significantly reducing stowed volume while enabling each wing to generate up to 25 kW of power²²⁸. MegaFlex’s design relies primarily on hinged ribs, where one-third to one-half of each rib folds onto the remaining section, minimizing stowed height. The deployment sequence begins with the unfolding of the ribs, followed by the fan-like extension of the array blanket. Notably, the inner rib segments do not support photovoltaic array, increasing the overall deployable radius, and hence gaining in PV area.²⁵¹ With current launch vehicle capabilities, the achievable array sizes for MegaFlex™ range from 10 kW to 1 MW, making it a scalable solution for future high-power space applications.²⁵²

CONCLUSIONS AND OUTLOOK

FUTURE DIRECTIONS AND CHALLENGES OF FLEXIBLE AND LIGHTWEIGHT SOLAR ARRAYS

As space missions demand efficient, compact, and high-performance power solutions, flexible and lightweight solar arrays have emerged as a key enabler for next-generation spacecraft and space habitats. Looking ahead, future PVA developments will focus on enhancing power-to-mass ratio, improving radiation resistance, and enabling scalable deployment mechanisms suitable for diverse mission profiles. For example, future space exploration faces unprecedented challenges, particularly in extreme environments such as Venus, where high temperatures, corrosive atmospheres, and intense radiation rapidly degrade conventional spacecraft materials.^{253,254} Additionally, looking beyond lunar and Martian colonization to deep-space missions targeting distant moons and asteroids, solar cell wings should not constrain spacecraft design, especially when are integrated with electric or thermoelectric propulsion systems, which typically produce plasma ejection or plumes during operation.^{255,256} In these future scenarios, the main space agencies are actively investing in next-generation solar technologies to improve spacecraft autonomy and durability. These advancements include the maturation of emerging flexible devices integrated with origami-inspired deployable solar arrays and structures for compact storage and reliable deployment^{257–260}, radiation-resistant materials to withstand the combining effect of high-energy particle exposure and extreme temperatures^{261,262}, and hybrid energy systems integrating solar arrays with advanced batteries and fuel cells to provide continuous power.^{263–266} Within these future scenarios, hybrid perovskite, organic, and CIGS flexible solar cell are gaining momentum as potential enablers, but despite their notable mechanical flexibility and specific power, these solar cells still face critical challenges in achieving long-term reliability under the harsh conditions of space.^{23,43,267} As a result, their near-term deployment is expected in less demanding environments such as high-altitude pseudo-satellites (HAPS) and very low Earth orbits (VLEO), which serve as ideal platforms for performance validation and gradual de-risking. To provide a structured overview of their status and potential application, a SWOT analysis is presented in **Table 12**. Building upon these emerging technologies, it is also important to consider the next wave of innovation that could define the future of space lightweight photovoltaics. Transition metal dichalcogenide (TMD)-based solar cells, for instance, show projected efficiencies close to 22% and specific power values exceeding 3000 W/kg for encapsulated and scalable modules.²⁶⁸ These projections are consistent with earlier experimental studies, which reported flexible WSe₂ solar cells delivering specific power values up to 4400 W/kg, with modelling indicating a theoretical upper limit exceeding 40000 W/kg.²⁶⁹ While they currently lack spaceflight qualification or analogous Earth-based testing, TMDs could play a significant role in shaping future space device architectures.

Table 12. SWOT analysis of emerging PV technologies for space applications: Perovskite, organic and CIGS solar cells.

Category	Key Points
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<u>Strengths</u>	✓ High specific power, especially for perovskite devices. ✓ Mechanical flexibility enables use in deployable, rollable, or inflatable structures. ✓ Low-temperature processing allows cost-effective, scalable fabrication of perovskite and OPV solar cells. ✓ CIGS devices exhibit strong space heritage and high efficiency under AM0 conditions. ✓ Compatibility with unconventional surfaces and small platforms (e.g. CubeSats, space probes). ✓ Self-healing behaviour in the case of perovskite and organic solar cells under specific temperatures and radiation profiles. ✓ Integration with other solar cell technologies to fabricate highly efficient tandem devices.
<u>Weaknesses</u>	○ Limited long-term radiation and thermal resilience under vacuum, especially for organic and perovskite devices. ○ Encapsulation remains a critical challenge for maintaining stability in vacuum, UV, atomic oxygen and plasma environments. ○ Lower average efficiency compared to III-V 3J technologies. ○ Difficulty in achieving consistent performance over large areas, particularly in organic and perovskite modules. ○ High vulnerability to interfacial degradation and mechanical fatigue under operational stress conditions.
<u>Opportunities</u>	➤ Integration in high-altitude pseudo-satellites (HAPS) and stratospheric balloons where conditions are less harsh than orbit. ➤ Suitability for disposable, low-cost satellites and short-lifetime missions (e.g., CubeSats). ➤ Supporting new mission architectures (e.g., inflatable wings, tethered solar sails). ➤ Strong momentum in terrestrial R&D may lead to rapid maturation and technology transfer. ➤ Lightweight power systems for lunar and Mars surface use (unmanned devices, small probes and autonomous aircrafts) ➤ Potential fabrication in space. ➤ Integration to future space intelligent fabrics or smart textiles.
<u>Threats</u>	• Stringent qualification requirements for space heritage limit their fast adoption. • Existing dominance of well-established III-V and Si-based technologies. • Regulatory and material restrictions (e.g., lead in perovskites and selenium in CIGS) may hinder adoption. • Vulnerability to micrometeoroids, atomic oxygen, and high-energy particles. • Lack of standardized testing protocols for emerging PVs under space conditions. • Anomalous behavior of perovskite materials due to their intrinsic softness nature.

Deployable solar technologies

One of the most promising innovations in flexible solar arrays is the development of origami-based folding mechanisms, which allow compact stowage and efficient, smooth deployment in space. One of the earliest proofs of concept for this technology was JAXA's Miura fold design, tested under the Two-Dimensional Solar Array Experiments program on the Space Flyer Unit, an Earth observation satellite launched in 1995²⁷⁰. In the last decade, various origami-inspired designs have been further refined for application in future lunar and planetary missions.^{271,272} For example, NASA's Jet Propulsion Laboratory (JPL) and Brigham Young University (BYU) have been collaborating on a design called Hanaflex over the last decade, showing potential high specific power value of around 300 W/kg for this design.^{211,258} In the same line, a young Italian company called Astradyne SRL is fabricating origami-based solar arrays for CubeSats. Utilizing a novel textile-based substrate, they are aiming for a specific power of above 120 W/kg.²⁷³ Complementary to these promising foldable architectures, NASA and its innovation programs, has supported companies in developing novel and lightweight deployable architectures. Among them, Opterus Research and Development, Inc. is advancing the R-ROMA (Retractable–Rollable Mast Array), a 50 kW-class flexible solar array with Solestial's devices designed for vertical deployment and retraction.²⁷⁴ This system features a trussed collapsible tubular mast (CTM) and composite flexible blanket elements, providing a compact, lightweight, and efficient solution for lunar power generation. Similarly, Ceres Robotics Inc. is developing C-Tower, a truss-based solar array with a vertical central mast that supports deployable and retractable solar panels.²⁷⁵ C-Tower can extend at least 10 meters above the lunar surface, generating up to 60 kW (BOL). Besides minimizing lunar dust interference, it potentially can reach a specific power exceeding 120 W/kg and a specific volume of ~45 kW/m² (BOL), offering a promising solution for future lunar and Martian energy needs. For orbital missions such as Earth observation or planetary exploration, small flexible arrays are being developed to support scientific instruments with low energy demands. Two examples of these small wings are the Composite Beam Roll-up Array (COBRA) and the EXOTERRA roll-out array, having a high-specific-power solar array designed for deep space CubeSat applications. By integrating the photovoltaic assembly with a deployable composite boom structure, they can achieve over 265 W/kg and

140 W/Kg at the array level, respectively.^{276,277} Alongside these innovations, booms and flexible arrays with inflatable architecture offer a wide range of possibilities for lightweight, high-power solar arrays.²⁷⁸ One promising concept, already extensively explored, is ITSAT (Inflatable Torus Solar Array Technology), which utilizes an inflatable toroidal structure to achieve high power output with minimal mass and compact stowage.²⁷⁹ By combining L'Garde's next-generation stretched aluminum inflatable rigidizable tube technology with Northrop Grumman's advanced polymer cover-glass photovoltaic cell technology, the ITSAT could achieve power densities of up to 105 W/Kg in a 0.5 kW-class solar array.

Radiation-resistant solar arrays

As space missions venture deeper into harsh and unpredictable environments, the demand for advanced power systems that can withstand high radiation levels while maintaining high performance and reliability is steadily increasing. One promising direction is the integration of radiation-resistant materials and architectures into flexible solar arrays, enabling lightweight, resilient, and compact energy solutions suitable for both near-Earth and deep-space missions. Coverlay engineering and new device architectures, can be considered part of the main approaches in paving the way to stable lightweight solar wings. Companies like The Aerospace Corporation have been investigating ultralight solar cells shielding using composites or hybrid materials/layers showing promising behavior compared to standard cover glasses for LEO and GEO spacecrafts.²⁸⁰ Regarding to solar cells advancements, nanowire-based (NW) solar cells and silicon-based self-healing devices are expected to play a significant role in the development of next-generation radiation-hardened power supply systems. Early studies in NW devices are highlighted the high potential of their nanometric architecture (100-200 nm wires), exhibiting damage thresholds ranging from 10–40 times higher than planar control solar cells when subjected to proton and electron irradiation, 100–350 keV and 1 MeV respectively^{281,282}. This remarkable performance has been achieved since the III-V semiconductor nanowires in the solar cell minimize the volume exposed to damage, maintain performance even with some defects, localize any radiation damage, and potentially handle thermal and mechanical stress better than a bulky layer. With respect to silicon solar cells, research efforts of Solestial and the French Alternative Energies and Atomic Energy Commission (CEA) have opened promising technological prospects for radiation-hardened flexible solar arrays.^{283–285} Traditionally, annealing radiation damage in silicon requires high temperatures (above 200–250°C), which are not typically encountered in space. However, Solestial's solar cells validated by CEA can effectively suppress radiation damage at approximately 90°C under standard sunlight illumination. This temperature aligns with the operating conditions of solar panels in low Earth orbit (LEO), making the self-healing process feasible during normal operation²⁸⁶. This recovery mechanism is attributed to defect engineering within the ultrathin (~20 µm) silicon cell, primarily through optimized doping profiles and passivation layers, which enables radiation induced defects to rearrange and neutralize at moderate operating temperatures, thereby restoring part of the device's performance. Additionally, after exposure to radiation levels equivalent to a 10-year mission in LEO, the solar cells exhibited only a 4% drop in open-circuit voltage, maintaining 96% of their initial performance. This resilience surpasses that of conventional III-V multijunction solar panels, which typically experience a 10–15% efficiency loss under similar conditions according to the CEA's validation study. While this latter statement is based on industrial validation rather than peer-reviewed reporting, it highlights the growing potential of ultrathin silicon devices as competitive alternatives to established III–V architectures in LEO applications.

Planetary and atmospheric exploration platforms

Flexible solar arrays will play a key role in planetary colonization, supporting habitats, and science airborne platforms in the oncoming decades. NASA's Lofted Environmental and Atmospheric Venus Sensors (LEAVES) exemplify how lightweight, flexible solar panels can be integrated to power aerodynamic probes and inflatable atmospheric balloons, enabling prolonged exploration of Venus' hostile conditions from high altitudes where solar irradiation is more favorable.²⁸⁷ Similarly, in the case of Earth applications at very low Earth orbit (VLEO), stratospheric platforms like balloons and airships will require lightweight, high-efficiency solar arrays to power long-duration missions and services. Emerging technologies such as air-breathing electric propulsion systems, which will use atmospheric oxygen to generate thrust, will depend on ultra-lightweight solar panels to guarantee its prolonged operation.²⁸⁸ These innovations are particularly relevant for future Earth observation, climate monitoring, and global communications networks, helping to reduce

costs and avoid congestion in LEO. Looking beyond Earth, Mars' missions will also benefit from inflatable solar powered platforms to provide power to surface operations from higher altitudes, avoiding the dust accumulation that commonly impairs solar cell performance. These platforms may work in conjunction with hybrid systems incorporating radioisotope thermoelectric generators to provide continuous power. On the surface, these systems are gaining renewed attention for their ability to provide uninterrupted power during eclipse periods, planetary/lunar nights, or in shadowed regions^{289–291} The integration of hybrid systems with flexible solar arrays enhances both adaptability and operational lifespan. By enabling controlled deployment and retraction, these arrays can minimize exposure to dust buildup and micrometeorite strikes, especially during inactive or dark phases. Such functionality makes them ideal for supporting rovers, landers, and surface habitats in the challenging terrains of rocky planets.

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AUTHOR CONTRIBUTIONS

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DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this review paper.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

During the preparation of this work the author(s) used ChatGPT in order to identify any grammatical errors in the text. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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