Power Systems for Small Satellites

Joseph N. Pelton and Scott Madry

Contents

1 Introduction 190
2 General Approach to the Design of a Small Satellite 192
3 Power Generation for Small Satellites 193
4 Solar Cell Systems for Small Satellites 193
5 Electric Power System Design and Wiring 194
6 Assembly, Integration, and Testing (AIT) 197
7 Conclusion 197
8 Cross-References 198
Annex 1 199
Photovoltaic Cell and Solar Array Suppliers 199
Representative Photovoltaic Cell Manufacturers 199
Solar Panels and Array Manufacturers 200
Innovative Solutions in Space (ISIS) 201
Cross-References 202
References 202

Abstract

The satellite power system is a vital component of all satellites and involves a number of parts. All of these parts play an important role in the success or failure of a small satellite mission. Since electrical power systems have been around since the beginning of the space age, and their function has been well established,

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

S. Madry
The University of North Carolina at Chapel Hill, Chapel Hill, NC, USA
e-mail: madrys@email.unc.edu

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_9

this part of a satellite design for this reason might be taken for granted. It also may be outside the expertise of cubesat builders with limited experience. This is a serious problem, as many telecommunications systems, on the ground or in space, often fail due to a power failure. This can be not only because the power generation or storage system fails but for other seemingly mundane factor such as a simple short in a wiring system that causes a satellite to fail due to a lack of critical power supply or even an electrical fire that destroys the entire satellite. Other sources of failure can come from as simple a problem as the leads from solar cells or photovoltaic cells failing due to contamination or oxidation that creates an overall power failure for a satellite. Experience over the years have confirmed the need to carefully design, manufacture, and test all aspects of a satellite's electrical power system in terms of safety, resilience, and lifetime performance. This important work is often overlooked or minimized in cubesat projects.

This chapter discusses all aspects of electrical power generation, an electrical power distribution system, power storage, and effective design of an electrical power system for all types of satellites that range from a femtosat (10 to 100 grams), a picosat (100 grams to 1 kg), a nanosat (from 1 kg to 10 kg) that includes cubesats, a microsat (from 10 kg to 100 kg), and a minisat (from 100 kg up to 500 kg in some definitions and from 100 to 1000 kg in others). The point is that power systems can command a good deal of the mass and volume of a satellite regardless of its size, and thus the power-to-mass ratio is important in satellites designs and especially so in the case of small satellites. Different approaches to power can thus be taken for different types of small satellites depending on their mission, lifetime requirements, and overall mass and volume. Finally, this chapter seeks to provide information developed by NASA and other objective sources about the suppliers of critical elements of an electrical power system for small satellites and especially with regard to solar power cells and power storage units.

Keywords

Assembly · integration · and test (AIT) processes · Batteries · Electrical power system (EPS) · Electrical power generation · Electrical wiring · Photovoltaic cells · Power management and distribution (PMAD) · Power storage · Power-to-mass ratio · Rechargeable secondary battery · Single and multi-junction solar cells · Single-use primary battery · Solar arrays and panels · Solar power cell · Solar cell junctions of · Spacecraft safety

1 Introduction

The overall design of a small satellite is largely driven by its power budget. This is because it is not atypical for one-third of the overall mass of a spacecraft to be related to its power supply and electrical systems. This is especially true if the spacecraft is being designed to have a sustained lifetime that lasts for a number of years. The application also drives the power requirements, and many satellites require significantly larger power systems than others. It is a mistake to look at the design of a small satellite's electrical power system as simply choosing which solar cells to select or which batteries to purchase. The equation is more complex than this. One should start with the key basics of the small satellite's mission; the smallsats intended lifetime; the orbital configuration in terms of whether it is a LEO, MEO, or GEO orbit; and other parameters. This will fundamentally drive your understanding of the mission objectives and parameters that will define what type of power system is required for your specific needs and budget.

If it is to be a telecommunications or networking mission in low Earth orbit with at least an 8-year lifetime and a particular throughput objective, then this can next allow a reasonable design process for the spacecraft. This initial set of objectives can next lead to developing a reasonable concept as to antenna design as required by the mission, as well as the power requirements, the fuel and thruster system to support the intended lifetime, etc. If it is to be a remote sensing or data analytics project, then there is a need to define basic objectives for revisit times, level of sensor resolution and types of sensors, data storage and data transmission, projected satellite lifetime, and more.

Again, these mission goals and objectives will lead to a clear system definition that can produce a better understanding of the type of satellite to be designed. This includes the power requirements needed to complete the intended mission. In short, one does not start with power requirements. Rather mission goals and resulting design features will serve to define the acceptable boundaries of the power system and clarify its various design features.

On one end of the scale, a short experimental project with a limited lifetime and minimal transmission requirements might result in a single-use primary battery that might be sufficient to provide the needed power until the battery is exhausted and solar cells or other power generation capabilities may not be needed at all. Operational missions with extended lifetimes will clearly require rechargeable batteries, on-board power generation, a process for discharging and maintenance of batteries, a monitoring function to observe the performance of batteries, solar cells, computers, and much more. The redundancy requirements must also be considered.

Overall, the mission objectives will drive the power system design. A radar satellite system that uses active sensing and thus the ability to release power from the spacecraft that can be reflected back to the space will clearly require more power and internal shielding than a passive system that simply analyzes light reflected back from the sun. Active RADAR satellites were famous in the early days of the space era for frying themselves due to the large power pulses required. Early Soviet military RADAR satellites were even powered by nuclear systems to meet these power requirements.

The key elements that designers of the mission will have to consider are (i) power generation; (ii) power storage; and (iii) overall electrical power grid and distribution requirements for the satellite payload (or payloads), as well as for the operation of the satellite bus. The power system design will tend to be different depending on the nature of the mission goals and objectives and clearly different for different types of satellites from the smallest of femtosats (or chipsats), up to the largest of minisats that might be as large as 500 kg or even 1000 kg.

Currently, a large percentage of small satellites have power generation capability and rechargeable batteries. cubesats on up tend to have such a capability. Even pocketqube systems at one-eighth the size of a 1-unit cubesat still have at least four solar cells and operate with a rechargeable battery. One chipsat or femtosat tends to have a single-use primary battery such as might be used in a wristwatch.

Thus, this discussion will start with a consideration of power generation and the predominant form that is used in most small satellites – namely, photovoltaic cells or, as they are more generally known, solar cells.

2 General Approach to the Design of a Small Satellite

There are actually several possible approaches that might be taken with regard to the design, assembly, integration, test, and launch of a small satellite project. One might be planning to design, build, and deploy a very large constellation of small satellites. In this case of an industrial applications project, one might create a vertically integrated system that creates all of the capabilities in-house and proceed to design and build perhaps hundreds or thousands of small satellites in-house. This is the case with SpaceX, Planet, and Spire, for instance. Another approach for an industrial satellite project would be to contract with an overall contractor that will obtain components, either to precise technical specifications or performance characteristic, and manufacture the small satellites for delivery for launch.

In the case of more individualized small satellite projects, one might obtain a complete kit for an entire small satellite from a vendor such as Pumpkin, or in the case of a larger and more sophisticated supplier, from some experienced entity such as Surrey Space Technology, Ltd. The other approach is to custom design and integrate all of the subsystems of a small satellite project in-house. The organization known as Innovative Solutions in Space (ISIS) operates a web-based Cubesat Shop. This is marketed as webshop for cubesats and nanosats and offers over 100 products associated with small sat projects. This website is broken down into the multiple parts or subsystems. These subsystems include antennas, attitude actuators, attitude sensors, cameras and payloads, command and data handling, communications systems, cubesat kits and buses, cubesat structures, ground stations, ground support systems, integrated attitude determination and control systems (ADCS), launch adapters, propulsion and pressurization, software services, solar panels and power systems, and training and simulators. Under these 16 categories, one can find multiple suppliers that correspond to each of these project subsystems. If one is new to the small satellite project area and wants assistance and guidance with regard to all these areas, the cubesat shop can be a useful source of information and guidance to legitimate and qualified suppliers from around the world (ISIS-cubesat Shop 2019).

3 Power Generation for Small Satellites

Although there are some small satellites that might use radioisotopes as a power source, such as planetary probes, and there are some missions that operate with a single-use non-rechargeable battery, these are only a minor exception to the general rule that most small satellites use solar cells to generate power and rechargeable batteries to store energy for the times when the spacecraft is in eclipse. The orbital parameters, including the period of solar eclipse, are vital parameters in the choice of these components.

4 Solar Cell Systems for Small Satellites

Solar cells, or photovoltaic cells, have been used to generate on-board power for satellite from the start of the space age. Consistent progress has been achieved over the decades to improve the efficiency of this technology in their ability to convert the energy from solar radiation into useful electrical power. At the start of the space age, these cells used amorphous silicon and typically had an efficiency of conversion of only about 10% to 13%. Today single P-N junction solar cells used in many solar panels for generating electrical power for homes and offices on Earth perform at comparable levels. Improved performance solar cells that use multiple junctions to capture energy at higher energy levels up to even the ultraviolet spectrum of energy are progressively more efficient, but also more expensive. A depiction of a positive-type to negative-type silicon junction that creates an electron flow is shown in Fig. 1.

The relatively higher performance of multi-junction solar cells that can capture energy at the higher energy green, blue, violet, and even ultraviolet spectra can clearly generate more electrical energy. There has been a careful study undertaken by NASA scientists to identify high-efficiency solar cells that use multi-junction photovoltaics and also solar cells that use high valence number and more efficient semiconductors using materials such as gallium arsenide, germanium, etc. to create

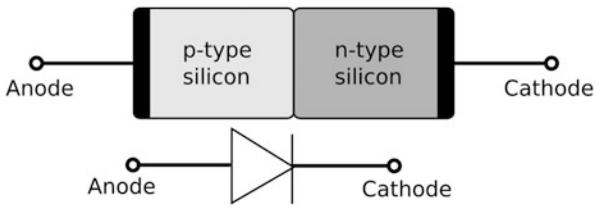

Fig. 1 Depiction of P-type/N-type silicon solar cell configuration. (Courtesy of Global Commons Raffa Maiden By Raffamaiden – BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=21285768)

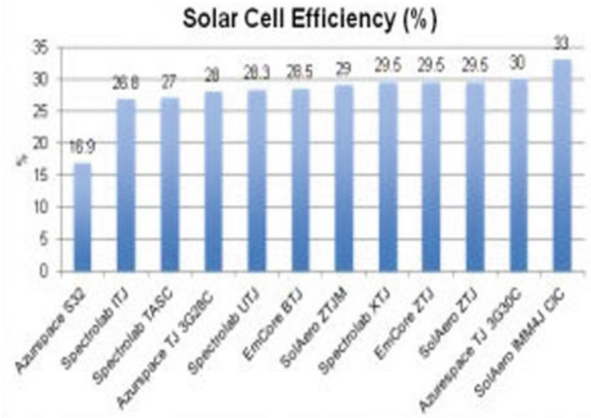

Fig. 2 A comparison of multi-junction solar cells that are possible candidates to use on small satellites. (Graphic courtesy of NASA)

performance efficiencies that are generally in the 26% to 34% levels. The results of these comparative studies are shown in Fig. 2 (NASA, State of the Art, 0.3 Power 2019).

A brief listing of different solar cell manufacturers and some of the key performance characteristics of their solar cell offerings are provided in Annex 1 at the end of this chapter (Table 1).

The convenience of solar panel designs which have been optimized for assembly integration and testing is not the only attractive feature. These panels can come with integrated magnetorquers for orientation and temperature and magnetometer sensors. In larger 3-units, additional integrated features can be integrated into the solar panel design as well. These panels can be obtained for side, top, and bottom cubesat designs. A 1-unit side panel as manufactured by DHV is pictured below. This unit is provided with wiring and connectors and is provided for around $1800 (US) and is available on order in about 4–5 weeks (Fig. 3) (DHV Technology 2019).

More demanding nanosat missions with higher electrical power system requirements can employ not only cubesat panels but deployable solar panels to increase the available electrical power supply. Deployable solar panels are more expensive and are only recommended in cases where the smallsat mission has greater energy needs to perform its intended mission. Below is a series of deployable arrays by EXA (Fig. 4).

5 Electric Power System Design and Wiring

There needs to be a systematic way to supply power to components of a small satellite with associated battery packs. This is a critical part of a small satellite design, assembly, integration, and testing process. Power failures, degraded solar cell performance, wiring disconnects, circuit breaker mishaps, switch-related problems, and other aspects of a satellite's overall power system that can fail represent a large portion of satellite failures of all types – large, medium, or small. Once in

Table 1 NASA assessed suppliers of solar panel suppliers. (Data provided by NASA)

NASA compilation of solar panel suppliers for pocketqubes (5 cm cubes) up to 12 U Cubesats				
Product	Manufacturer	Efficiency	Solar cells used	TRL status
Solar panel (0.5–12 U); deployable solar panel (1 U, 3 U)	Clyde Space	28.3%	Spectrolab UTJ	9
Solar panel (0.5–12 U); deployable solar panel (1 U, 3 U)	Clyde Space	29.5%	Spectrolab XTJ	9
Solar panel (0.5–12 U); deployable solar panel (1 U, 3 U)	Clyde Space	29.6%	Azur Space 3G30A	9
Solar panel (5 × 5 cm, 1 U, 3 U, custom)	DHV	29.6%	Azur Space 3G30C-Advanced	8
Solar panel	Endurosat	29.5%	CESI solar cells CTJ30	9
NanoPower (cubesat and custom)	GomSpace	29.6%	Azur Space 3G30A	9
HaWK	MMA	29.5–30.7%	SolAero XTJ Prime	7
eHaWK	MMA	29.5–30.7%	SolAero XTJ Prime	9
COBRA	SolAero	29.5%	SolAero ZTJ	Unknown
COBRA-1 U	SolAero	29.5%	SolAero ZTJ	Unknown
Space solar panel	Spectrolab	26.8%	SolAero ITJ	TRL 9
Space solar panel	Spectrolab	28.3%	SolAero UTJ	TRL 9
Space solar panel	Spectrolab	29.5%	SolAero XTJ	TRL 9
Space solar panel	Spectrolab	30.7%	SolAero XTJ Prime	TRL

Note: This assembled report by NASA scientists is as of the fall of 2019 and may not be complete in terms of including all possible suppliers from around the world. This chart is indicative of what international suppliers of solar arrays currently provide

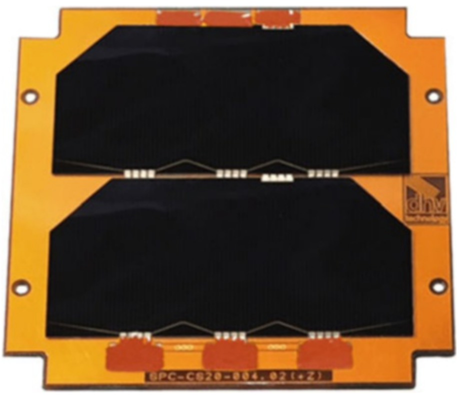

Fig. 3 DHV-CS 1-unit cubesat side panel with two solar units. (Graphic courtesy of DHV)

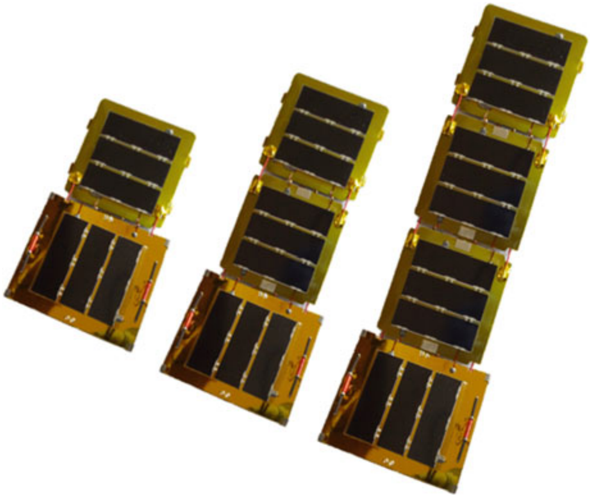

Fig. 4 Deployable solar array by EXA for high-power missions. (Graphic courtesy of EXA)

space, it cannot be understated that space is a hostile environment. Solar radiation and coronal mass ejections from the sun can and do lead to satellite failures by knocking out the power system. Circuit breakers and the ability to power down a satellite during a major solar storm event are something that large and more expensive satellites have as normal part of their operational routine. Small satellites should be operated with similar concern for these solar radiation and ion blast events from the sun.

One of the systems marketed via the cubesat store is the Crystalspace P1U EPS. This is a compact power supply with battery pack configured for both 1-unit and 2-unit cubesat configurations. This particular product includes a “fast maximum power point tracking boost converter.” This is able to charge integrated doubled battery pack and provide power distribution as required for cubesat configurations. Battery output in the electrical power system is fed through duplicated converters. Depending on the type of system ordered and solar array capabilities, these electrical power systems can provide voltage outputs starting at 3.3 V and up to 12 V. Pinouts and voltage outputs can be custom ordered in order to accommodate specific user needs (cubesat shop, Crystal Space 2019).

Another option is the Endurosat Electric Power System that also provides two battery packs and the following additional features: (i) three solar panel channels in order to provide a channel for each of the cubesats’ three axes and six panel connectors (typically USB connectors unless otherwise specified); (ii) input voltage (per solar panel channel) up to 5.5 V; (iii) input current (again this is for each of the three solar panel channels) up to 1.8 amperes; and (iv) a full guarantee of performance warranty and up to 5 hours of technical support (Endurosat 2019).

There are many other electrical power systems available such as the electrical power system including rechargeable battery packs from ISIS and many other suppliers that can be found on the web and those noted at the end of this chapter. It is important to work with suppliers if there are issues related to the US International Traffic in Arms Regulations (ITAR) or other similar restrictions in other countries such as the European Commission requirements. For the most part, these do not apply to the smaller-sized energy systems.

6 Assembly, Integration, and Testing (AIT)

The key elements of small satellite power systems include solar arrays or solar panels, electrical power systems with regulatory systems for power distribution that include battery packs, electrical wiring, sun sensors for maximum illumination, and magnetorques that can assist with sun orientation. The final missing ingredient is the process known as assembly, integration, and testing (AIT). It is important that well-trained personnel operating in clean rooms (or in some instances "clean enough rooms") carry out this important process. A faulty or somewhat loose wiring or USB plug connection can easily be shaken apart from a vital connection during the dynamic loads encountered during launch. Microsats or minisats for commercial systems are typically tested on shaker tables to simulate the vibrations and so-called pogo effects that can occur during rocket launch operations. After assembly is complete and the small satellite is completely integrated, careful testing is highly recommended. In the case of deployable antenna and power arrays, it is important to check out both of these deployments. Thus there needs to be a careful assessment of whether the antenna deployment and solar array deployments do not complicate or hinder either deployment process. Training of personnel to carry out all of these steps precisely and with quality checks along the way is important. In the case of large-scale small satellite constellations, many of these steps are now completely automated, but the test and assessment are still largely done by trained personnel.

7 Conclusion

The careful design and assembly, integration, and test of the electrical power system (EPS) are a key part of being able to create, launch, and operate a small satellite mission successfully. There are many elements of a satellite project, and it is easy to lose sight of an important step where there are so many parts to the puzzle. This article only addresses the design, assembly, integration, and test of the energy subsystem of a small satellite bus and its payload. It should be remembered that a successful program must also consider the ground stations and the mission control aspects of tracking, telemetry, control, and monitoring (TTC&M) of a mission. If there is a power failure in the ground segment, the mission could be lost in this way as well. Again power failures in the ground stations or the mission control are the most common types of problems that can and do occur in operational satellite systems.

The good news is that there are now many suppliers of small satellites. There are organizations such as Pumpkin and ISIS that can provide a complete cube satellite for launch and also assist with a launch services integrator that can arrange for a launch and launch registration and other administrative and regulatory arrangements from soups to nuts. Many cubesat and even smaller picosat (i.e., pocketqube) projects are training and learning exercises, and thus such projects tend to involve the design, assembly, and integration of all of the key subsystems in order to create an in-depth educational experience. It is important to consider the balance between gaining experience and education on one hand and assuring that "practical" quality assurances and mission goals are fully met on the other. Is this an educational, professional research, or business project? This is a fundamental question to be answered.

It is important to learn and understand about each and every subsystem and component that is essential to a small satellite programs' success. To recap, these elements include (i) antennas; (ii) attitude actuators; (iii) attitude sensors; (iv) cameras and payloads; (v) command and data handling; (vi) communications systems; (vii) cubesat kits and buses; (viii) cubesat structures; (ix) ground stations; (x) ground support systems and mission control; (xi) attitude determination and control systems (ADCS); (xii) launch adapters; (xiii) propulsion and pressurization; (xiv) software services; (xv) solar panels and power systems; and (xvi) training and simulators. Of all of these "parts" of a mission, a reliable, high-efficiency, and well-managed power system is well up there in terms of being a critical aspect of the mission with many single point-of-failure considerations and vulnerabilities.

8 Cross-References

- ▶ Flight Software and Software-Driven Approaches to Small Satellite Networks
- ▶ High Altitude Platform Systems (HAPS) and Unmanned Aerial Vehicles (UAV) as an Alternative to Small Satellites
- ▶ Hosted Payload Packages as a Form of Small Satellite System
- ▶ Network Control Systems for Large-Scale Constellations
- ▶ Overview of Small Satellite Technology and Systems Design
- ▶ RF and Optical Communications for Small Satellites
- ▶ Small Satellite Antennas
- ▶ Small Satellite Constellations and End-of-Life Deorbit Considerations
- ▶ Small Satellite Radio Link Fundamentals
- ▶ Small Satellites and Structural Design
- ▶ Spectrum Frequency Allocation Issues and Concerns for Small Satellites
- ▶ Stability, Pointing, and Orientation

Annex 1

Photovoltaic Cell and Solar Array Suppliers

There are a growing number of global suppliers of solar cells and complete solar arrays that include the solar cells with the integrated struts for ready deployment in space. Some manufactures such as Spectrolab can provide either individual solar cells or the fully integrated solar array. Research projects around the world are seeking to drive efficiency up about the current highest levels of around 45%. These research activities are exploring new high valence substrate and absorber materials, spectrum matching techniques, as well as lower-cost fabrication and new production techniques such as the IMM cell that uses metamorphic multi-junction manufacturing techniques. The following listing of multi-junction solar cell and solar array manufacturers is indicative of some of the well-known and tested suppliers.

Representative Photovoltaic Cell Manufacturers

Azur Space

This is a supplier of multi-junction solar cells that are typically triple-junction in design. These cells use a combination of gallium arsenide, germallium, and GaInP materials, and they achieve an efficiency of solar radiation to electrical energy output in the range of 28% to 30%.

Bharat Electronics Ltd. of India

Bharat Photovoltaics has developed its manufacturing capabilities in cooperation with the Indian Space Research Organization (ISRO). ISRO has licensed solar cell and solar panel technology from other suppliers in the USA and other countries and then partnered with Bharat Electronics Ltd. to create a lower-cost supply to the Indian market. Bharat can supply both solar cells and solar panels. These products include monocrystalline, polycrystalline, and thin-film solar cells. It also provides inverters, mounting systems, solar cables, as well as complete photovoltaic systems, terrestrial power systems, as well as satellite applications.

CESI/ENE

The CESI single-junction gallium arsenide solar cells that are deposited on a germanium wafer by ENE are thicker than some three-junction solar cells, but this lower-cost photovoltaic cell can provide a 20% efficiency under the AMO spectrum rating system. This type of cell has been used by the Surrey Space Technology Ltd for small satellite manufacture. Triple-junction solar cells with efficiencies around 27% are also available from these Italian and Belgium teams.

Emcore Corporation

Emcore also manufactures triple-junction solar cells in two different versions. The efficiency of solar energy conversion for these solar cells is typically in the range of

28.5% to 29.5%. Emcore cells are provided in standard sizes but can be provided to custom order in different sizes as well. NASA has used these cells on their own missions.

SolAero Technologies

SolAero Technologies is unique in that it is a collaborative effort with the US Air Force. SolAero Technologies and the USAF are currently developing a new type of cell known as the "metamorphic multi-junction (IMM)" solar cell. This special manufacturing technique has resulted in a lightweight and higher-efficiency cell that is in developmental testing. Current SolAero cell have an efficiency level in the 28% to 30% range. They offer at least four optional solar cell products with ZTJ cell having had extensive in-flight experience. The ATJ, ATJM, and BJT cells are particularly offered to support small spacecraft missions.

Spectrolab

This company has been one of the oldest and most comprehensive providers of solar cells as well as integrated solar arrays. There solar cells range in efficiency from 26% to 30%. The most common products by Spectrolab are the XJT Prime, XTJ, and UTJ solar cells. They are offered in standard and customized sizes. All of the Spectrolab's solar cells are also of the triple-junction design. The UTJ devices are rated at TRL 9 spacecraft applications.

Umicore

Umicore is another provider of triple-junction solar cells. It has been providing high-quality solar cells since the 1990s. Its solar cells with triple N-P junctions or bandgaps for its solar cells consist of indium gallium phosphide (InGaP), indium gallium arsenide (InGaAs), and germanium (GE) layer. These cells are made using a metal-organic chemical vapor deposition (MOCVD) process whereby the InGaP and InGaAs are deposited on germanium wafers. These solar cells have been demonstrated above 30% efficiencies under the AMO spectrum rating system.

Solar Panels and Array Manufacturers

Many of the companies that produce solar or photovoltaic cells also produce solar panels and arrays. In some instances, these panels also include magnetorquers, sun sensors, temperature sensors, and other features. Here are some of the typical providers of high-quality solar arrays from around the world. This is not an exhaustive list, but it includes many of the leading suppliers.

AAC Microtec and Clyde Space

The AAC Clyde Space photon solar arrays and solar panels are optimized to provide power to cubesat and multiple units of cubesats. These systems are designed to provide a high level of power generating efficiency by providing panels that can be position on the long sides of cubesats. If additional power is required, it is possible to have deployed, extendable solar arrays. These panels and arrays are designed to provide convenience in achieving reliable platform integration. Spectrolab XTJ Prime solar cells are typically included on AAC Clyde solar panels and arrays (AAC Clyde Space 2019).

Bharat Electronics Ltd.

See as noted in above information.

DHV Technology

DHV is one of the leading providers of solar panels and arrays. Its website maintains that it has participated in over 50 projects, that 35 satellites are currently utilizing its arrays and panels, and that this adds to some 1700 days of successful operation in space.

Endurosat

Endurosat makes several versions of solar panels. These are of a triple-junction indium gallium phosphide/gallium arsenide/germanium design and the solar cells used in these panels rated to 29.8% efficiency. The panels are of the 1-unit and 3-unit design, and their respective masses are 0.04 kg and 0.155 kg, and this includes a magnetorquer in the configuration. Maximum cell voltages are 2.33 V per cell (Endurosat, Solar Panels 2019).

EXA

The EXA DSA/1A (Titanium Deployable Solar Array for 1 U) is the entry-level product of a family of deployable solar arrays based on artificial muscles for cubesats in the range of 1 U to 6 U. The arrays are composed of five panels, 3 on top and 2 on the bottom, that are attached to the cubesat structure. Available on request are deploy and release contact sensors and also custom options such as sun and temperature sensors. Seven panel configurations are available for very high power missions.

GomSpace

GomSpace, which can undertake complete small satellites, is able to provide two different power systems for cubesats. These both use 30% efficient cells. These units are designed to include a magnetorquer, sun sensors, and gyroscopes. The customizable panels have a maximum output of 6.2 W and 7.1 W, respectively. Cubesat panels can be ordered with an integrated magnetorquer with only a slight mass addition. The 1-unit cubesat panel produces 2.3–2.4 W.

Innovative Solutions in Space (ISIS)

MMA Design, LLC

MMA's latest solar panel design is known as the rHaWK. It seeks to provide for high kW/m^3 solar electrical power production plus longer life, a high level reliability, through new manufacturing techniques significantly lower mass and volume. At the beginning of life, the MMA rectangular rHaWK solar panel can normally produce up to 90 kW/m^3 and at 28 °C over 150 W/kg. The efficiency rating for the solar cells used in the array is currently based on a configuration of the array at 29.5%. The lower-cost ZTJ cells produce 80 kW/m^3 and 130 W/kg at the beginning of life. MMA arrays have been used by both the US Air Force and NASA (MMA Design LLC 2019).

NanoAvionics

The solar panels provided by NanoAvionics are designed for 1-unit to 3-unit cube satellites. This array uses an epitaxial structure. These cells use a combination of gallium indium phosphide, gallium indium arsenide, and germanium for its structural makeup. Its solar panel efficiency is rated to be very close to 29%.

SolAero Technologies Corp

See as noted in above information.

Spectrolab

See as noted in above information.

Cross-References

► Small Satellite Radio Link Fundamentals

References

AAC Clyde Space, Photon Solar Panels. https://www.aac-clyde.space/assets/000/000/078/PHOTON_original.pdf?1564954830. Last accessed 15 Dec 2019

Cubesat shop, Crystal Space, 2019 PI U "Vasik". https://www.cubesatshop.com/product/crystalspace-p1u-vasik/. Last accessed 14 Dec 2019

DHV Technology. http://dhvtechnology.com/. Last accessed 14 Dec 2019

Endurosat, Electrical Power System Data Sheet. https://www.endurosat.com/modules-datasheets/EPS_Datasheet_Rev1.pdf. Last accessed 15 Dec 2019

Endurosat, Solar Panels. https://www.endurosat.com/modules-datasheets/Solar_Panel.pdf. Last accessed 15 Dec 2019)

Global Commons Raffa Maiden By Raffamaiden – BY-SA 3.0. https://commons.wikimedia.org/w/index.php?curid=21285768. Last accessed 20 Dec 2019

ISIS, Cubesat shop. https://www.cubesatshop.com/. Last accessed 13 Dec 2019

MMA Design LLC, rHawk Solar Panels. https://mmadesignllc.com/product/r-hawk-solar-array/. Last accessed 15 Dec 2019

NASA, State of the Art of Small Spacecraft Technology, 03. Power. https://sst-soa.arc.nasa.gov/03-power. Last accessed 14 Dec 2019