Chapter Contents

Chapter Glossary

(AFRL)	Air Force Research Laboratory
(BMS)	Battery Management System
(BOL)	Beginning-of-Life
(CFRPs)	Composite Fiber Reinforced Panels
(CIGS)	Cu(In,Ga)Se2
(COTS)	Commercial-off-the-Shelf
(EOL)	End-of-Life
(EPS)	Electrical Power System
(ESA)	European Space Agency
(GaN)	Galium Nitride
(GRC)	NASA Glenn Research Center
(KSC)	Kennedy Space Center
(Li-ion)	Lithium-ion
($LiCF_x$)	Lithium carbon monofluoride
(LiPo)	Lithium polymer
($LiSO_2$)	Lithium sulfur dioxide
($LiSOCl_2$)	Lithium thionyl chloride
(MIL)	Military
(QML)	Qualified Manufacturers List
(NiCd)	Nickel-cadmium
(NiH_2)	Nickel-hydrogen
(OPV)	Organic Photovoltaic
(OSCAR)	Optical Sensors based on carbon materials
(PCB)	Printed Circuit Board
(PEASSS)	Piezoelectric Assisted Smart Satellite Structure
(PET)	polyethylene terephthalate
(PMAD)	Power management and distribution
(RHUs)	Radioisotopic Heater Units
(RTGs)	Radioisotope Thermoelectric Generators
(SABER)	Solid-state Architecture Batteries for Enhanced Rechargeability and Safety
(SWaP)	Size, Weight, and Power
(TPV)	Thermophotovoltaic

(TR)	Thermoradiative
(TRL)	Technology Readiness Level
(Wh kg^{-1})	Watt hours per kilogram

3.0 Power

3.1 Introduction

The electrical power system (EPS) encompasses electrical power generation, storage, and distribution. The EPS is a major, fundamental subsystem, and commonly comprises a large portion of volume and mass in any given spacecraft. Power generation technologies include photovoltaic cells, panels and arrays, and radioisotope or other thermonuclear power generators. Power storage is typically applied through batteries; either single-use primary batteries, or rechargeable secondary batteries. Power management and distribution (PMAD) systems facilitate power control to spacecraft electrical loads. PMAD takes a variety of forms and is often custom-designed to meet specific mission requirements. EPS engineers often target a high specific power or power-to-mass ratio (Wh kg^{-1}) when selecting power generation and storage technologies to minimize system mass impact. The EPS volume is more likely to be the constraining factor for nanosatellites.

EPS Engineers should note the fundamental differences between commercial-off-the-shelf (COTS) parts and space qualified parts while weighing those differences against spacecraft requirements. Military or Space (MIL/QML) parts need to go through a series of specific tests, while COTS go through a different, typically less stringent, set of tests. For example, Military or Space parts are typically tested and qualified to survive -55°C to 125°C, while the alternative COTS requirement is -40°C to 85°C. SmallSat missions, especially CubeSat missions, don't always have a need to be qualified for harsh environments from a temperature perspective, as well as other factors that are a part of the MIL/QML qualification process like radiation, reliability, etc. COTS parts are typically known to perform better than space rated parts while lacking the ability to survive in harsh environments. Another key limitation in QML parts is their lack of availability and slow revision timeline. Most electronic components don't come with a QML version, and when they are available, QML parts tend to be multiple generations behind their COTS equivalents. All in all, MIL/QML parts can be a limiting factor in SmallSat designs, from their relatively weaker technical capabilities, to the increased costs associated with incorporating them into a design. CubeSats and other SmallSats typically operate at low-Earth orbit in a mild environment for short periods of time, and so stringent qualification standards and high Technology Readiness Level (TRL) don't tend to carry a lot of weight on those missions.

In this chapter, the terms SmallSat and CubeSat are often used in the same context, however it is important for the reader to be aware of the distinctions between the two types of spacecraft. Please refer to the introduction of this report for more information on the categories of SmallSats. CubeSats fall under the category of both microsatellites and nanosatellites and CubeSat missions commonly use COTS parts for space applications. Due to their exclusive use in low-Earth orbit applications, CubeSats are more likely to incorporate COTS parts as they typically feature shorter mission lengths, more favorable environmental conditions, and as a result need less stringent standards when qualifying parts. Knowing the distinction between a CubeSat and a SmallSat is necessary in determining the potential for incorporating COTS parts in a SmallSat design.

The information described below is not intended to be exhaustive but provides an overview of current state-of-the-art technologies and their development status for a particular small satellite subsystem. It should be noted that TRL designations may vary with changes specific to payload, mission requirements, reliability considerations, and/or the environment in which performance was demonstrated. Readers are highly encouraged to reach out to companies for further information regarding the performance and TRL of described technology. There is no intention of mentioning certain companies and omitting others based on their technologies or relationship with NASA.

3.2 State-of-the-Art – Power Generation

Power generation on SmallSats is a necessity typically governed by a common solar power architecture (solar cells + solar panels + solar arrays). As the SmallSat industry drives the need for lower cost and increased production rates of space solar arrays, the photovoltaics industry is shifting to meet these demands. The standardization of solar array and panel designs, deployment mechanisms, and power integration will be critical to meet the desire of large proliferated constellations.

In SmallSat missions especially, cost and scheduling considerations are something that EPS engineers must pay attention to on a component level, and power generation components are no exception from this. When possible, choosing a pre-designed and qualified panel is preferred over designing unique solar panels to reduce the cost and schedule as well as unforeseen design and manufacturing issues. Companies that have capacity for mass production and automation are rare because space solar arrays, cells, and panels have always been a 'boutique' business; however, standardized designs have been appearing more often these days to meet the demands of highly proliferated constellations, with a couple examples being the OneWeb and StarLink constellations.

3.2.1 Solar Cells

Solar power generation is the predominant method of power generation on small spacecraft. As of 2021, approximately 85% of all nanosatellite form factor spacecraft were equipped with solar panels and rechargeable batteries. Limitations to solar cell use include diminished efficacy in deep-space applications, no generation during eclipse periods, degradation over mission lifetime (due to aging and radiation), high surface area, mass, and cost. To pack more solar cells into the limited volume of SmallSats and NanoSats, mechanical deployment mechanisms can be added, which may increase spacecraft design complexity, reliability, as well as risks. Photovoltaic cells, or solar cells, are made from thin semiconductor wafers that produce electric current when exposed to light. The light available to a spacecraft solar array, also called solar intensity, varies as the inverse square of the distance from the Sun. The projected surface area of the panels exposed to the Sun also affects power generation, and varies as a cosine of the angle between the panel and the Sun.

While single junction cells are cheap to manufacture, they carry a relatively low efficiency, usually less than 20%, and are not included in this report. Modern spacecraft designers favor multi-junction solar cells made from multiple layers of light-absorbing materials that efficiently convert specific wavelength regions of the solar spectrum into energy, thereby using a wider spectrum of solar radiation (1). The theoretical efficiency limit for an infinite-junction cell is 86.6% in concentrated sunlight (2). However, in the aerospace industry, triple-junction cells are commonly used due to their high efficiency-to-cost ratio compared to other cells. Figure 3.1 illustrates the available technologies plotted by energy efficiency at the beginning-of-life (BOL) performance.

The current state of the art for space solar cells are multijunction cells ranging from 3 to 5 junctions based on Group III-V semiconductor elements (like GaAs). SmallSats and CubeSats typically use some of the highest performing cells that provide efficiencies up to 29% and 32%, even though they have a substantially higher cost than terrestrial silicon solar cells (~19% efficient). Ultimately the size, weight and volume of smaller satellites may be the determining factor in choosing solar cell technology. Being a life-limiting component on most spacecraft, the end-of-life (EOL) performance at operating temperature is critical in evaluating their performance. Common factors that degrade the functionality of solar cells include radiation exposure, coverglass/adhesive darkening, contamination, and mechanical or electrical failure.

This section individually covers small spacecraft targeted cells, fully-integrated panels, and arrays. Table 3-1 itemizes small spacecraft solar cell efficiency per the available manufacturers. Note the efficiency may vary depending on the solar cells chosen.

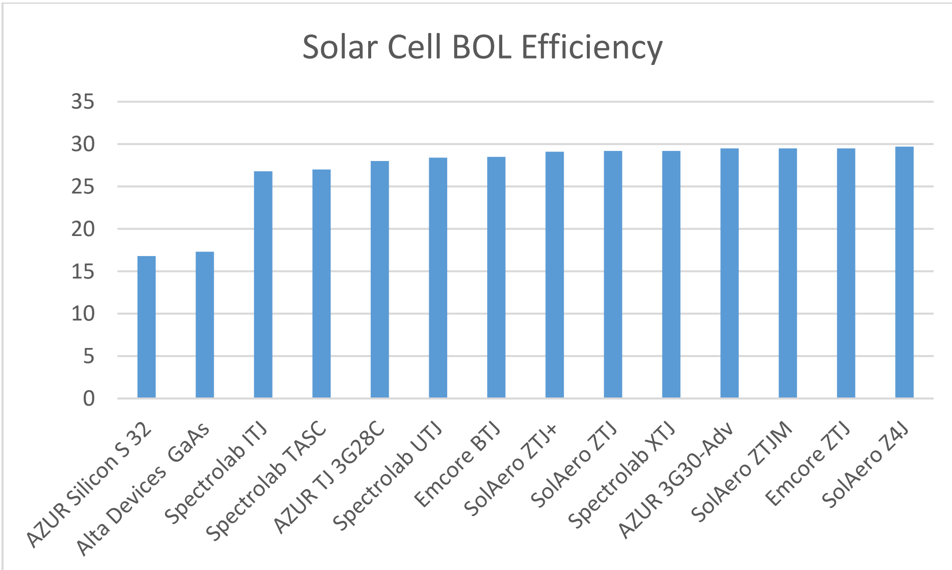

Figure 3.1: Solar cell efficiency. Credit: NASA.

Table 3-1: Solar Cells Product Table

Company	Cell Name	BOL Efficiency	Voc (V)	Vmp (V)	Jsc (mA/ cm^2)	Jmp (mA/ cm^2)	Pmp (W/m^2)	Citation
AZUR Space	Silicon S 32	16.8	0.628	0.528	45.8	43.4	229.2	(3)
	3G30-Adv	29.5	2.7	2.411	17.2	16.71	403	(3)
	4G32-Adv	31.5	3.426	2.999	15.2	14.37	431	(3)
	TJ 3G28C	28	2.667	2.37	16.77	16.14	1367	(3)
SolAero	ZTJ	29.2	2.726	2.41	17.4	16.5	397.7	(10)
	ZTJ+	29.1	2.69	2.39	17.1	16.65	397.9	(10)

	ZTJ Omega	29.9	2.73	2.43	17.4	16.8	408.2	(10)
	Z4J	29.7	3.95	3.54	12	11.5	407.1	(10)
	IMMα	31.7	4.78	4.28	10.7	10.12	433.1	(10)
	ZTJM	29.5	2.72	2.38	17.1	16.5	392	(10)
SpectroLab	XTJ	29.2	2.633	2.348	17.8	17.02	399.6	(6)
	XTJ-Prime	30.4	2.715	2.39	18.1	17.4	415.9	(6)
	XTE-SF	31.9	2.75	2.435	18.6	17.8	433.4	(5)
	XTE-HF	31.8	2.782	2.49	18	17.4	427.9	(5)
	XTE-LF	31.3	2.755	2.459	18.1	17.4	427.9	(5)
	UTJ	28.4	2.66	2.35	17.14	16.38	384.93	(7)
	TASC	27	2.52	2.19	32	28	270	(8)
	ITJ	26.8	2.565	2.27	16.9	16	1353	(9)
Emcore	BTJ	28.5	2.7	2.37	17.1	16.3	386	(4)
Emcore	ZTJ	29.5	2.726	2.41	17.4	16.5	397	(4)

3.2.2 Solar Panels & Arrays

Solar panels & arrays are constructed from individual solar cells connected in series to form strings and in parallel to form circuits mounted on a substrate backing (e.g., figure 3.2). While very low power CubeSats and SmallSats may only need body-mounted solar panels, most will require more power from deployed solar arrays. The deployed solar arrays for CubeSats and SmallSats are mostly on rigid substrates made of either a Printed Circuit Board (PCB), Composite Fiber Reinforced Panels (CFRPs), or an aluminum honeycomb panel.

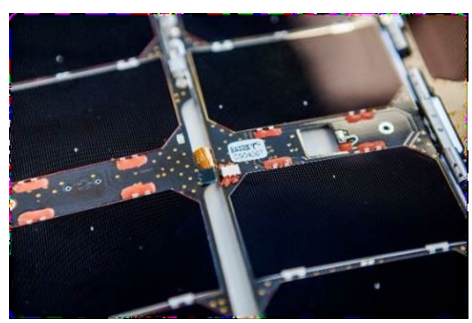

Figure 3.2: AAC Clyde Space solar arrays. Credit: AAC Clyde Space.

Deployed solar arrays are often the largest structure on a satellite; the ratio between the size of the deployed solar array and the size of the SmallSat may be much higher compared to other conventionally large spacecraft. The size and fundamental frequency of the solar arrays impact spacecraft pointing, propulsion, and delta-V needed for station keeping. Important considerations for SmallSat solar arrays are: deployment mechanisms, deployed frequency, panel specific power, and power density, as well as stowed volume. Most of these metrics are not listed on manufacturer's data sheets.

Solar array comparison can be challenging because SmallSat/CubeSat manufacturers who make solar arrays specific to their bus and payload designs often do not report solar array power using the same metrics. Their reported "power" can mean multiple things: power available to the payload, peak power provided by a combination of solar array and battery, or an orbital specific average power. Solar array power (Peak BOL) reported in the chart is mainly referring to the peak power of the solar array at the beginning of life, 28°C which is mission-independent. Panel stiffness and moment of inertia are dependent on multiple factors such as size and mass of the panel as well as spacecraft size and weight distribution, and usually need to be calculated for a specific spacecraft.

Table 3-2: Solar Array/Panel Products

Company	Product	Panel Type	Specific Power (W/kg)	Peak BOL Solar Array Power (W)	TRL	Citation
AAC Clyde Space	Photon	Body Mount + Deployed Rigid	*	9.25W / 3U Face	7-9	(11)
Blue Canyon Technologies	BCT Solar Array	Body Mount + Deployed Rigid	*	28 – 42 (3U) / 48-118 (6U-12U)	7-9	(12)
DHV Technologies	Solar Panels for CubeSats Set	Deployed Rigid (PCB)	67	0.272-60 (1P/1U/3U/6U/12U)	N/A	(13)
Exoterra	Fold Out Solar Arrays (FOSA)	Deployed Flexible	140	150	5-6	(14)
MMA Design	Hawk	Deployed Rigid (PCB)	121	36-112	7-9	(15)
	zHawk	Deployed Rigid (PCB)	95	36	7-9	(16)
Airbus Defense and Space Netherlands	Sparkwing Solar Panel	Deployed Rigid	165	66	5-6	(17)
Agencia Espacial Civil Ecuatoriana	DSA/1A	Deployed Rigid	107	7.2	7-9	(18)

GomSpace	Nanopower DSP	Deployed Rigid	*	1.2	7-9	(19)
ISISPACE	Smallsat Solar Panels	Body Mount + Deployed Rigid	46	2.3W / U	7-9	(20)
Redwire Space	ROSA	Flexible PV blanket	100	1000	5**	(21)
	Aladdin SmallSat Array	Hybrid Array: Flex Rigid	80	300	5-6	
EnduroSat	1U Solar Panel	Deployed Rigid	50	2.4	7-9	(35)
	1.5U Solar Panel	Deployed Rigid	55	2.4	7-9	
	3U Solar Panel/Array	Deployed Rigid	66	8.4	5-6	
	6U Solar Panel/Array	Deployed Rigid	64	19.2	5-6	
Nanoavionics	CubeSat GaAs Solar Panel	Deployed Rigid	Unk	Unk	7-9	(89)

* Available with Inquiry to Manufacturer

** For smallsat use

3.3 On the Horizon – Power Generation

New technologies continue to be developed for space qualified power generation. Promising technologies applicable to small spacecraft include advanced multi-junction, flexible and organic solar cells, hydrogen fuel cells and a variety of thermo-nuclear and atomic battery power sources.

3.3.1 Multi-junction Solar Cells

Fraunhofer Institute for Solar Energy Systems has developed different four-junction solar cell architectures that currently reach up to 38% efficiency under laboratory conditions, although some designs have only been analyzed in terrestrial applications and have not yet been optimized (Lackner). Fraunhofer ISE and EV have achieved 33.3% efficiency for a 0.002 mm thin silicon based multi-junction solar cell, and future investigations are needed to solve current challenges of the complex inner structure of the subcells (22). Additionally, SpectroLab has been experimenting with 5- and 6-junction cells with a theoretical efficiency as high as 70% (23).

A collaboration between the Air Force Research Laboratory (AFRL) and SolAero has developed Metamorphic Multi-Junction (IMM-α) solar cells that have been shown to be less costly with increased power efficiency for military space applications (1). The process for developing IMM-α cells involves growing them upside down, where reversing the growth substrate and the semiconductor materials allows the materials to bond to the mechanical handle, resulting in more effective use of the solar spectrum (1). A single cell can leverage up to 32% of captured sunlight into available energy. This also results in a lighter, more flexible product. These cells had their first successful orbit in low-Earth orbit in 2018, and since then they have operated in low-Earth orbit on other CubeSat missions.

3.3.2 Flexible Solar Cells

Flexible and thin-film solar cells have an extremely thin layer of photovoltaic material placed on a substrate of glass or plastic. Traditional photovoltaic layers are around 350 microns thick, while thin-film solar cells use layers just one micron thick. This allows the cells to be flexible, lightweight, and cheaper to manufacture because they use less raw material. The performance of commercial flexible CIGS was investigated and reported in relation to potential deep space applications at the University of Oklahoma. The authors found promising thin film solar material using Cu(In,Ga)Se2 (CIGS) solar cells with record power conversion efficiencies up to 22.7% (24).

3.3.3 Organic Solar Cells

Another on the horizon photovoltaic technology uses organic or “plastic” solar cells. These use organic electronics or organic polymers and molecules that absorb light and create a corresponding charge. A small quantity of these materials can absorb a large amount of light making them cheap, flexible and lightweight.

Toyobo Co., Ltd. and the French government research institute CEA have succeeded in making trial organic photovoltaic (OPV) small cells on a glass substrate. Trial OPV modules on a lightweight and thin PET (polyethylene terephthalate) film substrate were demonstrated during their joint research project. Toyobo and CEA succeeded in making the OPV small cells on a glass substrate with the world’s top-level conversion efficiency by optimizing the solvents and coating technique. In a verification experiment under neon lighting with 220 lux, equivalent to the brightness of a dark room, the trial product was confirmed to have attained a conversion efficiency of about 25%, or 60% higher than that of amorphous silicon solar cells commonly used for desktop calculators (25).

In October 2016, the Optical Sensors based on carbon materials (OSCAR) stratospheric-balloon flight test demonstrated organic-based solar cells for the first time in a stratospheric environment. While more analysis is needed for terrestrial or space applications, it was concluded that organic solar energy has the potential to disrupt “conventional” photovoltaic technology (26). Since then, a joint collaborative agreement between the German Aerospace Center and the Swedish National Space Board REXUS/BEXUS has made the balloon payload available for European university student experiments collaborating with European Space Agency (ESA) (27).

No standardized stability tests are yet available for organic-based solar cell technology, and challenges remain in creating simultaneous environmental influences that would permit in-depth understanding of organic photovoltaic behavior, but these achievements are enabling progress in organic-based solar cell use. In 2018, Chinese researchers in organic photovoltaics were able to reach 17% power conversion energy using a tandem cell strategy. This method uses different layers of material that can absorb different wavelengths of sunlight, which enable the cells to use more of the sunlight spectrum, which has limited the performance of organic cells (28).

3.3.4 Fuel Cells

Hydrogen fuel cells are appealing due to their small, light and reliable qualities, and high energy conversion efficiency. They also allow missions to launch with a safe, storable, low pressure and non-toxic fuel source. An experimental fuel cell from the University of Illinois that is based on hydrogen peroxide rather than water has demonstrated an energy density of over 1000 Wh kg^{-1} with a theoretical limit of over 2580 Wh kg^{-1} (29). This makes them more appealing for interplanetary missions and during eclipse periods, however unlike chemical cells, they cannot be recharged on orbit. Carrying a large fuel tank is not feasible for small or nanosatellite missions. Regenerative fuel cells are currently being researched for spacecraft application. Today, fuel cells are primarily being proposed for small spacecraft propulsion systems rather than for power subsystems (30).

3.3.5 Nuclear Power

Another source of spacecraft power comes from harnessing the energy released during radioactive decay. Radioisotope Thermoelectric Generators (RTGs) are associated with longer lifetimes, high reliability, predictable power production, and are more appealing beyond Mars orbit (>3 AU) than relying on batteries and solar panels. Unlike fuel cells, an RTG may operate continuously for decades without refueling. A full-sized RTG, such as on New Horizons, has a mass of 56 kg and can supply 300 W (6.3% efficiency) at the beginning of its life (31). Additionally, the Perseverance rover is being powered by a nuclear energy system known as Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) (90).

In addition to power generation, radioactive decay can also aid in offsetting the power requirements of SmallSats, allowing for smaller sized power generation and storage subsystems. Heaters are often one of the most power-hungry subsystems in space missions. An example of this is the Ingenuity Mars Helicopter which uses 90% of its power to heat its batteries and electronics. Radioisotopic Heater Units (RHUs) generate heat through the decay of plutonium-238 and can be used to keep SmallSat equipment warm, decreasing the load that conventional heaters have on the SmallSat electrical power system (32).

Although a radioisotope power system has not yet been integrated on a small spacecraft and may present challenges for SmallSats with limited mass and power requirements, options for nuclear power generation might be considered in the future (e.g., for small spacecraft missions that traverse interplanetary space). This concept would require substantial testing and modified fabrication techniques to facilitate use on smaller platforms. There are limits placed on the amount or mass of a radioisotope that can be used in a spacecraft before special handling and procedures are required. These limits are determined by values for specific types of radioactive material, but spacecraft designers should note that radioactivity levels below these values can be flown in spacecraft without any special handling. NASA/TM—2018-219940 gives a summary of low-power radioisotope-based power sources and acceptable values (91).

3.3.6 TPV

A thermophotovoltaic (TPV) battery consists of a heat source or thermal emitter and a photovoltaic cell which transforms photons into electrical energy. Thermophotovoltaic power converters are similar to high TRL thermoelectric converters, but the latter uses thermocouples and the former uses infrared-tuned photovoltaic cells.

A planar TPV system with very high efficiency and output power has been numerically demonstrated at near-field at large vacuum gaps, illustrated in figure 3.2. As a performance example, the 50 W scale-up TPV power supply with 1.5 kg of fuel has a projected weight specific energy density of 645 Wh kg^{-1}. This is 4 times larger than for a Li-ion battery (33).

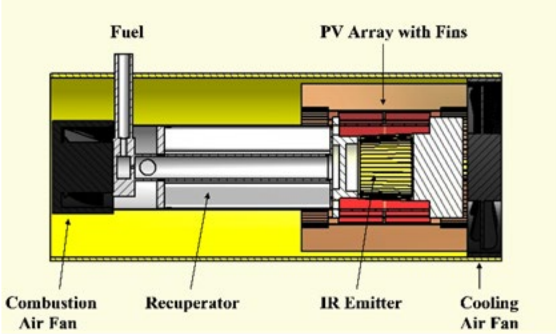

Figure 3.2: (top) Design of TPV power supply and (bottom) functional stand-alone TPV power supply. Credit: Fraas et al. (2017).

3.3.7 Alpha- and Beta-voltaics

Alpha- and beta-voltaic power conversion systems use a secondary material to absorb the energetic particles and re-emit them via luminescence. These photons can then be absorbed by photovoltaic cells. Methods for retrieving electrical energy from radioactive sources include beta-voltaic, alpha-voltaic, thermophotovoltaic, piezoelectric and mechanical conversions. This technology is currently in the testing/research phase.

3.3.8 Thermoradiative (TR) Cells

In the opposite way to which conventional solar cells deliver power through absorbing light from the sun, thermoradiative cells generate power through the emission of light. In practice, photons emitted by a blackbody near room temperature have far less energy than the bandgap of silicon, so these devices are constructed with ultralow-bandgap materials which, in ideal cases, can produce as much as 54 W m^{-2} (10 W m^{-2} in practical cases), compared to the 200 W m^{-2} that is descriptive of modern commercial silicon solar cells. Despite yielding less power generation than regular solar cells, TR cells have the advantage of being able to generate power in shaded conditions, which lends itself to waste heat recovery, as well as being able to aid in preventing and recovering from spacecraft anomalies like a dead bus. Additionally, TR cells happen to perform the best in space where the lack of an atmosphere prevents losses due to absorption by the atmosphere. Researchers at University of California, Davis are currently testing and characterizing the limits of these devices. In the future TR cells could be pivotal in being able to extract electrical power from the radiative emission of thermal wavelengths from a device on earth to outer space (34).

3.4 State-of-the-Art – Energy Storage

Solar energy is not always available during spacecraft operations; the orbit, mission duration, distance from the Sun, or peak loads may necessitate stored, on-board energy. Primary and secondary batteries are used for power storage and are classified according to their different electrochemistry. As primary-type batteries are not rechargeable, they are typically used for short mission durations. Silver-zinc are typically used as they are easier to handle and discharge at a higher rate, however there are also a variety of lithium-based primary batteries that have a higher energy density, including: lithium Sulfur dioxide ($LiSO_2$), lithium carbon monofluoride ($LiCF_x$) and lithium thionyl chloride ($LiSOCl_2$) (36).

Secondary-type batteries include nickel-cadmium (NiCd), nickel-hydrogen (NiH_2), lithium-ion (Li-ion) and lithium polymer (LiPo), which have been used extensively in the past on small spacecraft. Lithium-based secondary batteries are commonly used in portable electronic devices because of their rechargeability, low weight, and high energy, and have become ubiquitous on spacecraft missions. They are generally connected to a primary energy source (e.g. a solar array) and can provide rechargeable power on-demand. Each battery type is associated with certain applications that depend on performance parameters, including energy density, cycle life and reliability (36). A comparison of energy densities can be seen in figure 3.3, and a list of battery energy densities per manufacturer is given in table 3-3.

This section will discuss the individual chemical cells as well as pre-assembled batteries of multiple connected cells offered from multiple manufacturers. Due to small spacecraft mass and volume requirements, the batteries and cells in this section will be arranged according to specific energy, or energy per unit mass. However, several other factors are worth considering, some of which will be discussed below (37).

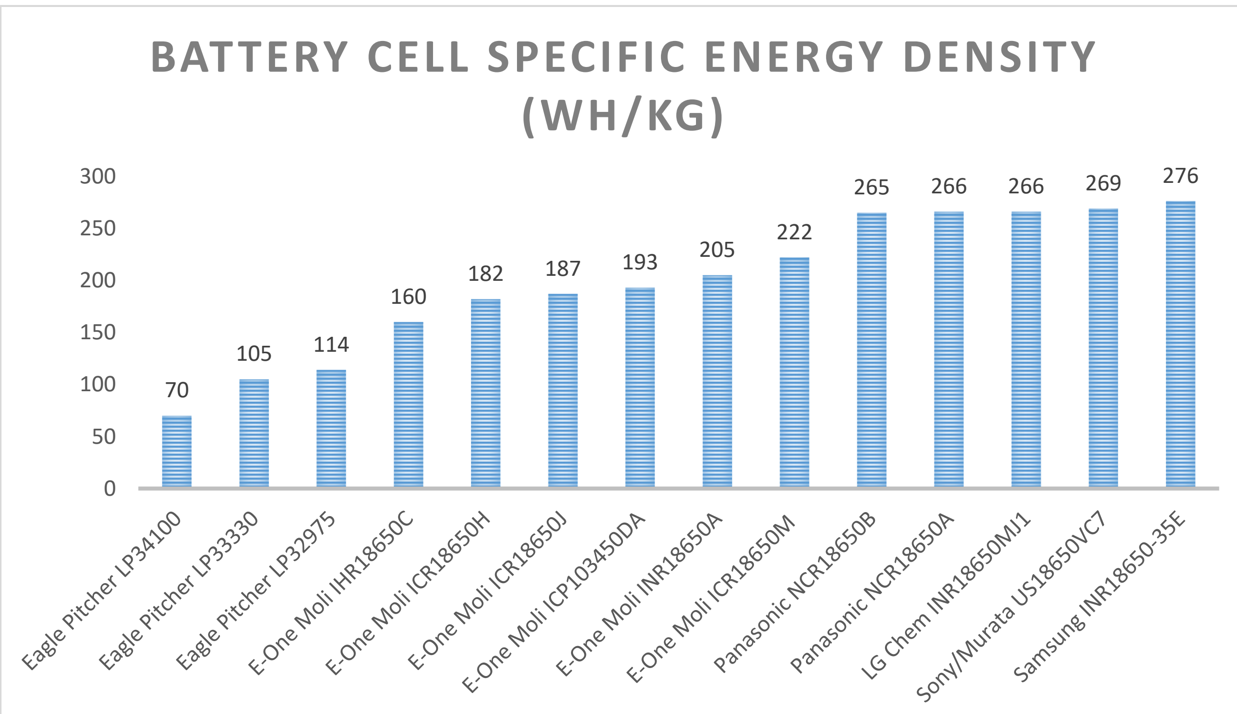

Figure 3.3: Battery cell energy density. Credit: The Aerospace Corporation.

Table 3-3: Battery Product Table								
Company	**Product**	**Volumetric Energy Density [Wh L^{-1}]**	**Specific Energy [Wh kg^{-1}]**	**Typical Capacity [Ah]**	**Max Discharge Rate [A]**	**Cells Used**	**TRL**	**Citation**
EaglePicher Technologies	NPD-002271	271	153.5	14.5	15	EaglePicher Li-ion	7-9	(39)
GomSpace	Nanopower BPX (4S-2P)	228.7	150	5.2	2.5	GomSpace NanoPower Li-ion	7-9	(42)
GomSpace	Nanopower BP4 (2S-2P)	211.9	149.2	5.2	2.5	GomSpace NanoPower Li-ion	7-9	(43)
AAC Clyde Space	Optimus-40	169.5	119	4.84	2.6	Clyde Space Li-Polymer	7-9	(44)
Ibeos	28V Modular Battery	151.1	109.8	9.82	20	*	N/A	(45)
Saft	VES16 4S1P	109.2	91	4.5	4.5 – Cont. 9 - Pulse	SAFT Li-ion	7-9	(46)
Vectronic Aerospace GmbH	VLB-X	101.96	74.6	12	10 – Cont. 20 - Pulse	SAFT Li-Ion	7-9	(47)
Berlin Space Technologies	BAT-110 Modular Battery (Nominal 3 strings)	69.73	57.75	7.5	3	Li-Fe	7-9	(48)

* Available with Inquiry to Manufacturer

Table 3-4: Battery Cell Product Table							
Company	**Product**	**Volumetric Energy Density [Wh L^{-1}]**	**Specific Energy [Wh kg^{-1}]**	**Typical Capacity [Ah]**	**Max Discharge Rate [A]**	**Voltage Range [V]**	**Citation**
Samsung	INR18650-35E	733	276	3.4	8	2.65 – 4.2	(49)
Sony/Murata	US18650VC7	735	269	3.5	8	2 – 4.2	(50)
Panasonic	NCR18650A	620	266	3.1	3.9	2.5 – 4.2	(51)
	NCR18650B	730	265	3.35	6.4	2.5 – 4.2	(52)
LG Chem	INR18650MJ1	720	266	3.5	10	2.5 – 4.2	(53)
E-one Moli	ICR18650M	631	222	2.8	2.5	3 – 4.2	(54)
	INR18650A	520	205	2.5	20	2 – 4.2	(60)
	ICP103450DA	478	193	2.15	2.5	3 – 4.2	(58)
	ICR18650J	517	187	2.37	5	2.5 – 4.2	(57)
	ICR18650H	496	182	2.2	5	3 – 4.2	(56)
	IHR18650C	425	160	2.05	20	2 – 4.2	(55)
EaglePicher Technologies	LP32975	285	114	12	96	3 – 4.1	(41)
	LP33330	263	105	6	24	3 – 4.1	(40)
	LP34100	165	70	5	500 – Cont. 2000 - Pulse	3 – 4.1	(38)

* Available with Inquiry to Manufacturer

The chemistry and cell design impacts the volumetric and specific energy densities. This limit represents the total amount of energy available per unit volume or weight, respectively. Current top of the line Li-ion energy cells exhibit ~270 Wh kg^{-1}. Li-ion batteries exhibit lower energy densities due to inclusion of a battery management system (BMS), interconnects, and sometimes thermal regulation.

There are generally two groups of cells – high energy or high power. High power cells use a low resistance design, such as increasing coating surface area, or multiple points of contact for the current collector to cell which can allow for lower overall resistance values and a higher rate of discharge. High energy cells work to optimize gravimetric energy densities to obtain the most energy from the cell. Some common methods to increase gravimetric energy densities are via addition of silicon to the anode, use of high voltage cathodes, or using a metallic lithium anode. However, these methods can significantly reduce the cyclability of the battery system in exchange for increased energy density.

In general, for space applications, high energy density is important because a battery with high gravimetric energy density will be cheaper to launch into orbit (higher battery capacity per unit mass). However, for some high pulse applications, high power cells would meet mission needs with less weight. However, energy density is not the only factor to look into during cell selection. For non-space commercial applications, faster degradation (lower cyclability) of the battery can be beneficial as the electronic device often lasts as long as the battery, and faster turnover of a device may lead to increased revenue.

While space-designed cells typically underperform in energy density, they over-perform in cyclability with many space-designed cells used for longer (~5-15 year) missions. Of a limited number of COTS cells tested, NASA results for 40% low-Earth orbit testing showed that the LG MJ1 provides the best cyclability compared to some of its peers for 1500 cycles (61). However, not all degradation modes for lithium-ion trend in a linear fashion, and trends often take time to settle, thus the test results don't necessarily show the best performing cell until others are further along in testing.

Due to the extremely short mission durations with primary cells, the current state-of-the-art energy storage systems use lithium ion (Li-ion) or lithium polymer (LiPo) secondary cells, so this subsection will focus only on these electrochemical compositions, with some exceptions.

3.4.1 Secondary Li-ion and Li-po Batteries

Typically, Li-ion cells deliver an average voltage of 3.6 V, while the highest specific energy obtained is well in excess of 150 Wh kg^{-1} (37). Unlike electronics, battery cells do not typically show significant damage or capacity losses due to radiation. However, in an experiment done by JPL, some capacity loss is seen among these latest lithium ion battery cells under high dosage of Cobalt-60. The results are shown below in figure 3.4 (62).

In Lithium-ion batteries, repeated charging cycles of the battery eventually result in aging or degradation that affects the overall energy (Watt-hours) that the battery may provide. There are many variables that impact aging, such as temperature, charge/discharge rate, depth of discharge, storage conditions, etc. Due to the numerous variables that impact aging, lithium-ion batteries are typically put under life test in mission conditions prior to launch to ensure the battery will meet the specific mission life requirements.

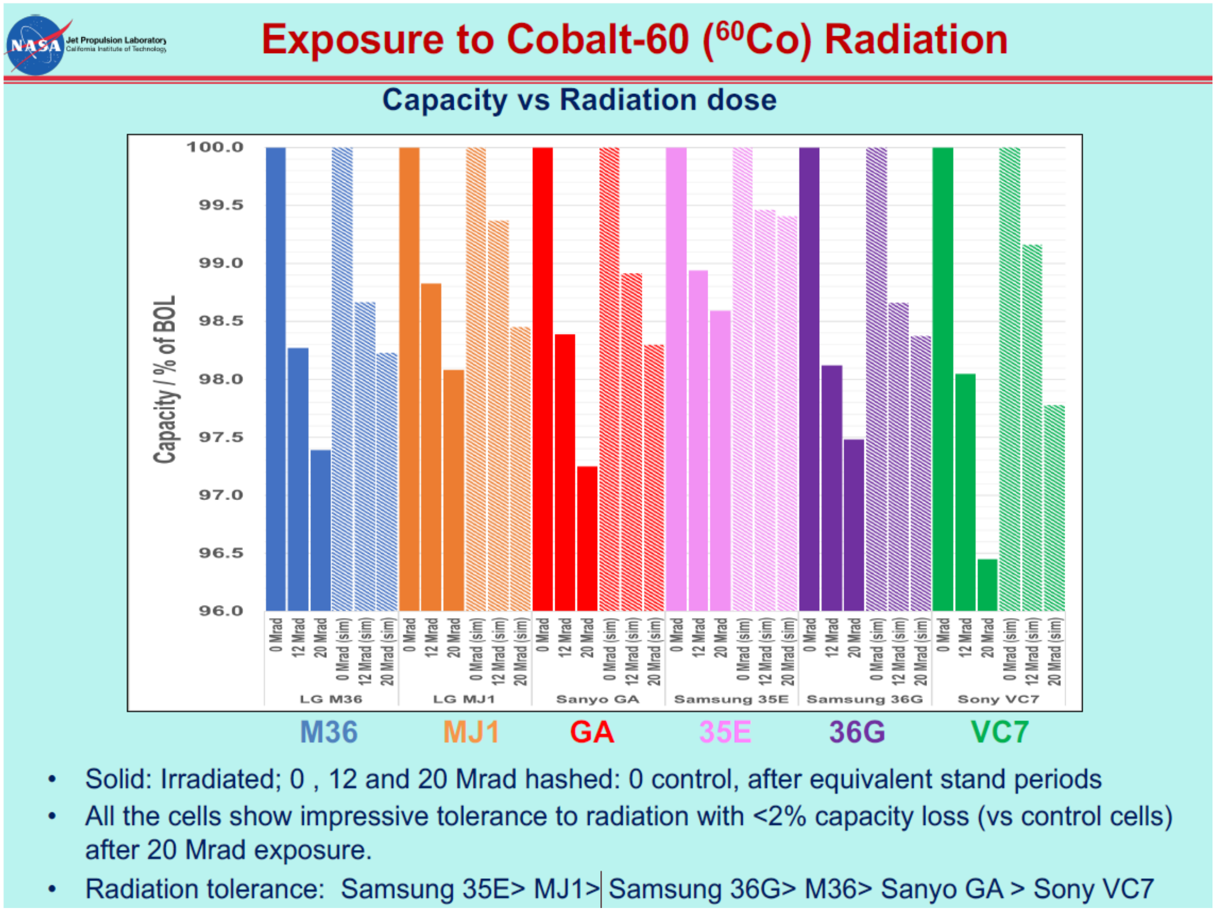

Figure 3.4: Capacity vs. radiation dose. Credit: JPL.

18650 Cells

18650 cylindrical cells (18 x 65 mm) have been an industry standard for lithium ion battery cells. Many manufacturers have staple high-performance 18650 cells, some of which have flown on multiple spacecraft and are documented in table 3-5 below.

Table 3-5: 18650 Cylindrical Cells

Cell	Specific Energy (Wh kg^{-1})	Flight Heritage
LG ICR18650 B3 (2600 mAh)	191	NASA’s PhoneSat spacecraft
Panasonic NCR18650B (3350 mAh)	243	N/A
Molicel ICR18650H (2200 mAh)	182	NASA’s EDSN mission
Canon BP-930s (3000 mAh)	112	NASA’s TechEdSat missions

Panasonic NCR18650GA (3450 mAh)	258	N/A
LG MJ1 (3500 mAh)	260	N/A

Cylindrical 18650s have become the most commonly used building blocks for many SmallSats today, although prismatic and pouch formats are also available. The lithium-ion industry has seen incremental increases in energy density via inclusion of silicon in the anode, high voltage cathodes, new electrolyte additives, and improved cell designs.

21700 Cells

21700 (21 x 70 mm) is another type of cylindrical cells that are getting more popular. Samsung 50E and LG M50 both offer 5000 mA h of energy while the Samsung cells are slightly heavier. The specific energy densities are 262 Wh kg^{-1} and 264 Wh kg^{-1} respectively. Although 21700 cells are slightly larger than 18650 cells, they are among some of the cells with highest energy densities. They could offer some mechanical packaging benefits with fewer cells for certain missions.

4680 Cells

4680 cells (46 x 80 mm) cylindrical cells are a form factor of battery cell that has been introduced to the energy storage scene by Tesla. The larger format cell potentially exacerbates several of the thermal management drawbacks (particularly internal temperature gradients and heterogeneity in current distribution) associated with other common smaller cells, however in order to address these drawbacks, Tesla has a "tabless current collection" method where the current collector foil is used in conjunction with an array of current collectors to reduce ohmic losses and the temperature increases that those losses can cause (63).

When it comes to the manufacturing of Li-ion batteries and battery cells, these companies are at the forefront for their respective sectors listed in table 3-6.

Table 3-6: Commercial and Space Li-ion Manufacturers			
Commercial Li-ion Manufacturing		**Space Li-ion Manufacturing**	
Company	**Headquarters**	**Company**	**Headquarters**
Panasonic	Japan	EaglePicher Technologies	USA
LG Chem	South Korea	Enersys	USA
Samsung	South Korea	GS Yuasa	Japan
E-one Moli	Taiwan	Saft	France
Sony	Japan		

3.5 On the Horizon – Energy Storage

In the area of power storage there are several on-going efforts to improve storage capability and relative power and energy densities; a Ragone Chart shown in figure 3.5 illustrates different energy devices (64). For example, the Rochester Institute of Technology and NASA Glenn Research Center (GRC) developed a nano-enabled power system on a CubeSat platform. The power system integrates carbon nanotubes into lithium-ion batteries that significantly increases available energy density. The energy density has exceeded 300 Wh kg^{-1} during testing, a roughly two-fold increase from the current state of the art. The results in this program were augmented from a separate high-altitude balloon launch in July 2018 organized through NASA GRC and showed typical charge and discharge behavior on ascent up to an altitude of 19 km (65). A collaborative project between the University of Miami and NASA Kennedy Space Center (KSC) is aiming to develop a multifunctional structural battery system that uses an electrolytic carbon fiber material that acts as both a load bearing structure and a battery system. This novel battery system will extend mission life, support larger payloads, and significantly reduce mass. While several panel prototypes have shown successively increased electrochemical performance, further testing of the individual components can improve the accuracy of the computational models (66).

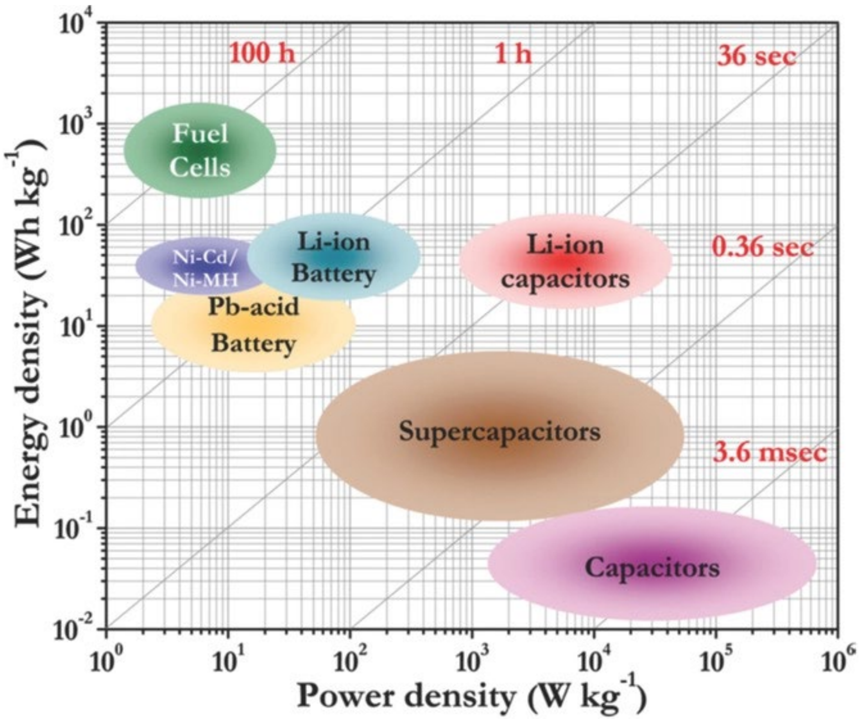

Figure 3.5 Relative power and energy densities of different energy devices. Ragone chart illustration reprinted with permission from Aravindan et al. Copyright (2014) American Chemical Society.

3.5.1 Supercapacitors

While the energy density for supercapacitors, also called ultracapacitors, is low (up to 7 Wh kg^{-1}), they offer very high-power density (up to 100 kW kg^{-1}). This property could be useful for space applications that require power transients. Their fast charge and discharge time, and their ability to withstand millions of charge / discharge cycles and wide range of operational temperatures (-40°C to +70°C), makes them a perfect candidate for several space applications (launchers and satellites). This was demonstrated in an ESA Study Contract No. 21814/08/NL/LvH entitled "High Power Battery Supercapacitor Study" completed in 2010 by Airbus D&S (67). Currently the Nesscap 10F component and a bank of supercapacitor based on the Nesscap 10F component are space qualified after the completion in 2020 of the ESA Study Contract No. 4000115278/15/NL/GLC/fk entitled "Generic Space Qualification of 10F Nesscap Supercapacitors". Although not likely to replace Li-ion batteries completely, supercapacitors could drastically minimize the need for a battery and help reduce weight while improving performance in some applications. Figure 3.6 shows a comparison chart (68), and table 3-4 lists differences in Li-ion batteries and supercapacitors (69).

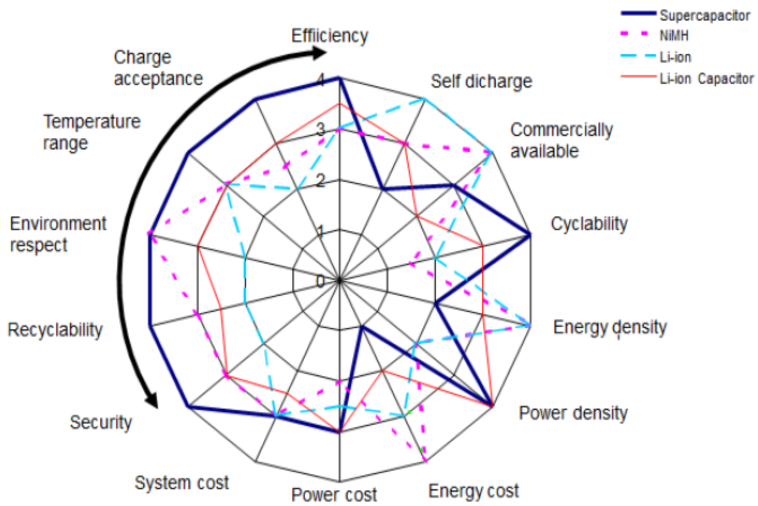

Figure 3.6: Supercapacitor comparison chart. Credit: Airbus Defense and Space and ESA (2016).

Table 3-7: Battery-vs-Supercapacitor Specifications		
Feature	**Li-Ion Battery**	**Supercapacitor**
Gravimetric energy (Wh kg^{-1})	100 – 265	4 – 10
Volumetric energy (Wh L^{-1})	220 – 400	4 – 14
Power density (W kg^{-1})	1,500	3,000 – 40,000
Voltage of a cell (V)	3.6	2.7 – 3
ESR (mΩ)	500	40 - 300
Efficiency (%)	75 – 90	98
Cyclability (nb charges)	500 – 1,000	500,000 – 20, 000,000
Life (years)	5 – 10	10 – 15
Self-discharge (% per month)	2	40 – 50 (descending)
Charge temperature	0 to 45°C	-40 to 65°C
Discharge temperature	yes	no
Deep discharge pb	yes	no

Overload pb	yes	no
Risk of explosion	yes	no
Charging 1 cell	complex	easy
Charging cells in series	complex	complex
Voltage on discharge	stable	decreasing
cost ($) per kW h	235 – 1,179	11,792

The lithium ion capacitor is a promising recent development in the world of energy storage, combining the energy storage capabilities of both lithium ion batteries as well as double layered capacitors, providing a middle ground between power density and energy density, but suffers from a limited cycle life. Some lithium ion capacitors have a minimum specific energy of 200 Wh kg^{-1} but are limited by a maximum specific power of <350 W kg^{-1} (88).

3.5.2 Solid State Batteries

A majority of the batteries being used in contemporary space applications are lithium ion batteries that use liquid electrolytes, however these batteries carry an inherent risk of combustion from physical damage as well as thermal runaway due to overcharge. As a result, spacecraft often carry parasitic weight in the form of cooling systems and housing units. Interest in battery designs that solve the issue of safety and improve on energy and power density have been an industry topic for a long time, ultimately leading the way to NASA's SABER (Solid-state Architecture Batteries for Enhanced Rechargeability and Safety) project which aims to create solid state batteries that have significantly higher energy than current state of the art lithium-ion batteries and would not catch fire or lose capacity over time. Current strides in this project include examination and testing on unique battery chemistries including sulfur-selenium and "holey graphene" (70).

3.6 State-of-the-Art – Power Management and Distribution

Power management and distribution (PMAD) systems control the flow of power to spacecraft subsystems and instruments and are often custom designed by mission engineers for specific spacecraft power requirements, however, several manufacturers have begun to provide a variety of PMAD devices for inclusion in small spacecraft missions. PMAD not only delivers power coming from energy sources (typically solar arrays in SmallSat applications), but also conditions energy as well, mitigating harmful transient disturbances and fault conditions from propagating downstream and hurting connected loads.

Several manufacturers supply EPS which typically have a main battery bus voltage of 8.2 V but can distribute a regulated 5.0 V and 3.3 V to various subsystems. The EPS also protects the electronics and batteries from off-nominal current and voltage conditions. As the community settles on standard bus voltages, PMAD standardization may follow. Well-known producers of PMAD systems that focus on the small spacecraft market include Pumpkin, GomSpace, Stras Space, and AAC Clyde Space. However, a number of new producers have begun to enter the PMAD market with a variety of products, some of which are listed below. Table 3-3 lists PMAD system manufacturers; it should be noted that this list is not exhaustive.

Key considerations in determining PMAD device selection often include conversion efficiency, input/output voltage range, output power capabilities, and size, weight, and power (SWaP). These metrics are critical to consider for good smallsat PMAD designs, but it is important to note that PMAD devices are best chosen to suit the exact application of the SmallSat mission. SmallSat missions are often short in duration and more flexible in terms of risk management than larger satellites, thus lending themselves to greater flexibility in design choices. One must leverage the benefits and risks to the mission at hand when choosing COTS PMAD systems, which may include the following:

- COTS PMAD may require less intensive integration and testing but have drawbacks to be addressed in a custom PMAD build
- Unnecessary features and peripherals (e.g., excess switching, fusing, current capability) can greatly increase SWaP metrics on a SmallSat
- Variability in designs of COTS PMAD devices means that important features and protections are not available in all devices (MPPT, Dead-bus protections, redundancy mechanisms, etc.)

Due to the variability of COTS PMAD options, many choice considerations, from internal power management topologies/materials to telemetry and protection options, are either included or omitted from products depending on the manufacturer. Internal power regulation topologies have traditionally been silicon-based, but relatively recent research into the performance improvements of GaN (Galium Nitride) topologies has increased the number of GaN-based PMAD options on the consumer market with the following benefits over their silicon counterparts:

- Ability to achieve high switching rates and lower switching losses, allowing for the downsizing of inductors and capacitors, and improving SWaP metrics
- Lack of gate oxide layer in GaN-based field effect transistors yields improvements in overall efficiency

It must also be noted that GaN-based PMAD options are not to be considered as drop-in replacements for silicon-based PMAD options, as despite the number of performance improvements, GaN architectures come with a variety of drawbacks including high complexity of control circuitry and lack of flight heritage.

In looking at the table below, one must note that there is no single COTS PMAD solution that can fit all needs of a mission at hand. In appealing to a broad range of applications, most COTS PMAD devices make sacrifices that can impact important metrics for SmallSats, including SWaP as well as the efficiency and quality of the power being managed. In choosing to use COTS PMAD devices, designers and system architects should be aware of, and try to minimize, unnecessary features not beneficial to the mission.

Table 3-6: Product of Power Management and Distribution Systems									
Company	**Product**	**Mass (kg)**	**Volume (cm^3)**	**Peak Power Output (W)**	**Input Voltages (VDC)**	**Output Voltages (VDC)**	**Max Efficiency**	**TRL**	**Citation**
Pumpkin	EPSM 1	0.300	250	160	8-55	3.3-50	98.5	9	(71)
AAC Clyde Space	Starbuck Micro	2.45	3968	120	28	28 / 5	97	9	(72)
	Starbuck Mini	5.90	13133	1200	*	22-34 / 5 / 8/ 12 / 15	*	9	(73)
	Starbuck Nano	0.086	140	*	*	3.3 / 5/ 12	*	9	(74)
GomSpace	P31U	0.100	127	30	0-8	3.3 / 5	96	9	(75)
ISISPACE	iEPS Type C	0.360	14.13	13	12.8-16	3.3 / 5 / Unreg	95	9	(76)
DHV	EPS Module	0.177	1530	56	4.5-28	3.3 / 5 / 12 / Batt	93	9	(77)
Extreme Engineering Solutions (X-ES)	XPM-2020	0.660	400	300	22-29	3.3 / 5 / 12 / -12	90	N/A	(78)
EnduroSat	EPS I	0.208	183	10-20	0-5.5	3.3 / 5 / Batt	86	9	(79)
	EPS I Plus	0.292	259	30	0-5.5	3.3 / 5 / Batt	86	9	(80)
	EPS II	1.280	742	250	10-36	3.3 / 5 / 6-12 / Batt	89	9	(81)
Ecarver GmBH	PCU-SB7	1.500	1800	250	0-23.1	5	85	N/A	(82)

Berlin Space Technologies	PCU-110	0.960	1191	*	20-25	3.3 / 5/ 12 / 24 / 1.8-28	*	9	(83)
Ibeos	150W CubeSat EPS	0.140	124	150	18-42	3.3 / 5/ 12/ Unreg Batt	95	N/A	(84)
Nanoavionics	CubeSat EPS	*	*	175	2.6-18	3.3 / 5 / 3-18	96	N/A	(85)

* Available with Inquiry to Manufacturer

3.7 On the Horizon – Power Management and Distribution

Power management and distribution has been steadily improving each year due to changes in technology, as well as from different approaches to maximizing the usefulness of these systems, including modular architectures, wireless telemetry, and power transmission options.

3.7.1 Modular Architecture

For small spacecraft, traditional EPS architecture is centralized (each subsystem is connected to a single circuit board). This approach provides simplicity, volume efficiency, and inexpensive component cost. However, a centralized EPS is rarely reused for a new mission, as most of the subsystems need to be altered based on new mission requirements. A modular, scalable EPS for small spacecraft was detailed by Timothy Lim and colleagues, where the distributed power system is separated into three modules: solar, battery and payload. This allows scalability and reusability from the distributed bus, which provides the required energy to the (interfaced) subsystem (86).

ISISPACE has a modular EPS for CubeSat missions (3U+) that includes a large amount of flexibility in output bus options with adjustable redundancy for certain parts of the device. The modular EPS consists of a power conditioning unit for solar panel input, secondary power storage, a battery holder with integrated fuse, and a power regulation and distribution unit for subsystem loads. Each unit is designed to be independent, allowing for daisy chaining and flexibility in redundancy and subsystem upgrades. This device is based on heritage from the Piezoelectric Assisted Smart Satellite Structure (PEASSS) CubeSat flown in 2016, with the device itself having been successfully flown in 2018 (76).

3.7.2 Wireless Power Transfer and Telemetry

In the commercial world, the technology already exists for wireless sensing and power transmission from the order of microwatts, all the way up to kilowatts. In the realm of SmallSats, wireless power transfer/detection would be useful as redundant options in dusty environments where physical connectors can be contaminated, or in situations where hardware needs to be swapped around and powered (battery swaps). While wireless power transfer/detection is highly inefficient when compared to conventional means, research and development in this technology for use in space applications has a lot of potential in increasing the reliability and robustness of SmallSat power management and distribution.

3.8 Summary

Driven by weight and mostly size limitations, small spacecraft are using advanced power generation and storage technology such as >32% efficient solar cells and lithium-ion batteries. The higher risk tolerance of the small spacecraft community has allowed both the early adoption of technologies like flat lithium-polymer cells, as well as COTS products not specifically designed for spaceflight. This can dramatically reduce cost and increase mission-design flexibility. In this way, power subsystems are benefiting from the current trend of miniaturization in the commercial electronics market as well as from improvements in photovoltaic and battery technology.

Despite these developments, the small spacecraft community has been unable to use other, more complex technologies. This is largely because the small spacecraft market is not yet large enough to encourage the research and development of technologies like miniaturized nuclear energy sources. Small spacecraft power subsystems would also benefit from greater availability of flexible, standardized power management and distribution systems so that every mission need not be designed from scratch. In short, today’s power systems engineers are eagerly adopting certain innovative Earth-based technology (like lithium polymer batteries) while, at the same time, patiently waiting for important heritage space technology (like fuel cells and RTGs) to be adapted and miniaturized. Despite the physical limitations and technical challenges these power generation technologies have, most small and nanosatellites in the foreseeable future will still likely carry batteries to support the transient load.

For feedback solicitation, please email: arc-sst-soa@mail.nasa.gov. Please include a business email so someone may contact you further.

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