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14. ABSTRACT
As part of an ongoing effort to improve responsiveness of power systems to meet future mission needs in space, an independent survey of conventional and emerging power technology options has been conducted. In this paper, all power technology options, both generation and storage, have been organized, using figures of merit relevant to space systems, to provide a basis for more effectively matching power technology options to future mission requirements. The goal was to initially organize technologies based on overall energy content normalized to mass and volume at the component level as a generic means for comparison, recognizing that if mission specific features, such as system level packaging and integration designs, were included in this initial survey, a certain level of bias would have been introduced into the results.

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Survey of Current and Next Generation Space Power Technologies

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[Abstract] As part of an ongoing effort to improve responsiveness of power systems to meet future mission needs in space, an independent survey of conventional and emerging power technology options has been conducted. In this paper, all power technology options, both generation and storage, have been organized, using figures of merit relevant to space systems, to provide a basis for more effectively matching power technology options to future mission requirements. The goal was to initially organize technologies based on overall energy content normalized to mass and volume at the component level as a generic means for comparison, recognizing that if mission specific features, such as system level packaging and integration designs, were included in this initial survey, a certain level of bias would have been introduced into the results.

Nomenclature

α = alpha particles emitted from a radioactive source (i.e. ^{238}Pu)
β = beta particles emitted from a radioactive source (i.e. ^{63}Ni)
SOA = state-of-the-art
PV = photovoltaic
BOL = beginning of life
RTG = radioisotope thermoelectric generator

I. Introduction

In support of the military responsive space initiatives, there is a need to continue to improve responsiveness of power systems to meet future mission needs. Toward that end, there is a need to identify today's promising power technologies, both generation and storage, in order to ensure that adequate research resources are being applied to them to mature them to a useful level where they will be needed. The scope of this study therefore included power technologies that are fairly mature with either space or terrestrial heritage and could be used in the near-term with a small amount of development to promising, non-traditional, technologies that are less mature but could provide significant benefits in the longer term.

In order to identify candidate technologies, we drew upon data from the literature as well as input from subject matter experts. Each of the technologies were then organized according to specific figures of merit (or metrics), such as specific power, conversion efficiency, and maturity (Technology Readiness Level, TRL), with no attempt to rank or pre-screen. All sources of the information have been cited and there was no attempt to revise values with additional calculations or scaling. Since the technologies are at various states of development, some assumptions were made on component versus system level characteristics, performance and TRL. Unless stated otherwise, the approach has been to report values at a subsystem or component level of the specific power technology (this may or may not include the Power Management and Distribution (PMAD) element) and to consider technologies as individual components as opposed to combined, hybrid systems (system level metrics would consist of such items as: 1) mass (kg/kW), 2) deployed area (m^2/kW), and 3) volume (m^3/kW)). In addition, certain power technologies

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are more readily integrated into hybrid power configurations or other spacecraft functions, such as structure, and thereby gain an advantage in terms of the overall specific power rating. Although this type of “multi-functional” assessment is currently under evaluation, it has not been included in this paper.

As an example of a system level (as opposed to component level) comparison metric, consider batteries versus fuel cells. Packaging for batteries is already included in the specific energy density value whereas in the case of fuel cells, the fuel, fuel tank, reformer and other ‘packaging’ items may or may not have been included in the reported value. This becomes even more critical when evaluating the various technologies for various mission power requirements. Again, when comparing batteries and fuel cells, battery mass is directly proportional to mission energy requirements whereas in the case of a fueled system, the fuel tank and fuel are a function of the mission energy requirement and the converter mass is a function of mission power. Hence, the fueled system will have a higher specific energy density at higher power levels (refer to Fig, 1). For this reason, all power technologies have been organized at a component level.

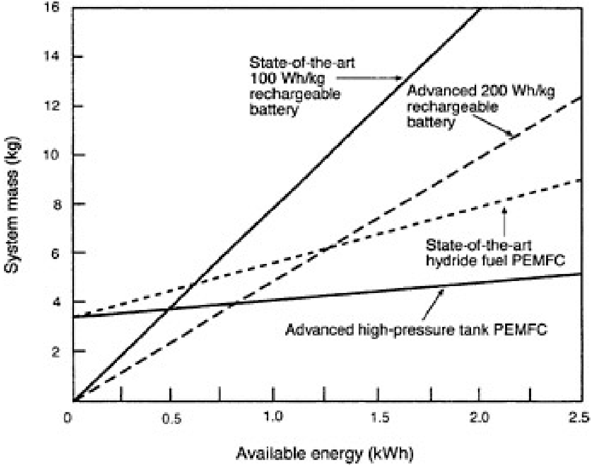

Figure 1. Available energy as a function of system mass for battery and fuel cell systems

II. Background

Almost all space missions to date have required some form of power onboard a spacecraft. The amount of power needed by these missions in the past, present, and future varies widely depending on the mission. Spacecraft operate as close as low Earth orbit, only hundreds of miles above Earth’s surface, and as far away as the outer planets and beyond. In the future, space missions may include a lunar base and a human mission to Mars. The power required for spacecraft ranges from watts to tens of kilowatts today and may require hundreds of kilowatts, even megawatts, in the future. The length of time that peak power is required also depends on the mission type. Some missions may require a few seconds burst of high power, while other missions may be conducted for decades, requiring continuous power for the entire mission life.

A variety of power system technologies can be used to satisfy this broad range of needs. The general applicability of a particular power system to a given power level and mission duration regime is depicted in Fig. 2[1]. The separate areas shown in the figure represent the areas where different power conversion technologies have the greatest benefit. For example, chemical systems, such as primary single use batteries, fuel cells, and combustion turbo alternators, are useful for relatively short lived missions. Solar photovoltaic systems using rechargeable batteries are in wide use today. Solar-heated, dynamic conversion systems are rarely used and are based on different thermodynamic cycles, such as the Brayton, Rankine, and Stirling cycles, alkali metal thermal electric converters (AMTEC) and thermionic converters. Finally, nuclear reactor- and radioisotope-heated dynamic and direct converters are listed. Thermoelectric and thermionic systems fall in this final category.

The shape of the boundaries between areas varies depending on the importance of power system mass, volume, cost, reliability, and system integration issues. Safety issues and other power system selection criteria can also affect the boundaries of the areas. In Fig.3, similar candidate power systems are grouped together in relation to their applicable regimes, showing selection criteria for one type of power system. Power system specific mass, defined as total mass divided by total power produced, is plotted versus power output for mission durations in the 5 to 10 year range. These optimum specific mass regimes were determined by plotting the results of the many space power system design studies conducted between 1960 and the 1990s.

A representative comparison of flight demonstrated power conversion technologies, representing current state-of-art, is presented in Table 1. This chart is a reasonable starting point for this study as all technologies are compared with an equal figure of merit. In this study, we updated the technology types in Table 1 to include more recent advances as well as inclusion of other potential technology candidates.

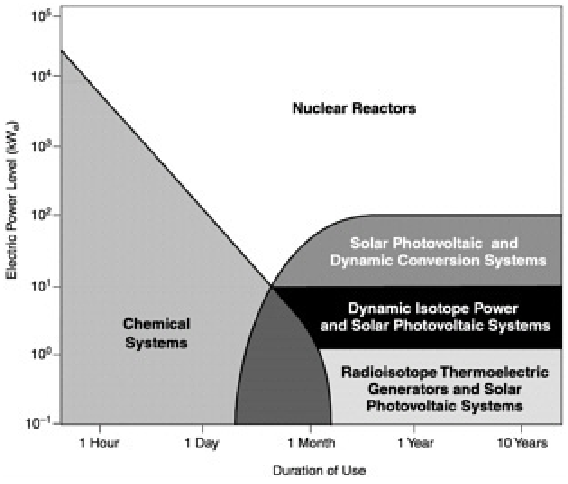

Figure 2. Power system options for specific mission durations.

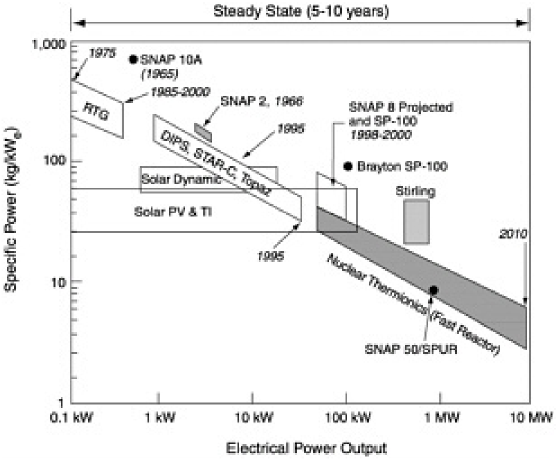

Figure 3. Inverse specific mass versus electrical power output.

Table 1. Comparison of Flight Demonstrated Power Conversion Technologies[1]

Technology	W/kg (BOL)	kg/kW (BOL)	Power Level (kW)	Recurring Cost ($/Watt)	Year	Life (yr)	Comments
Photovoltaic	14.85	67.36	10	1,130			- Good between Mars and Venus
- solar array	50.00	20.00		700	2000	15	- Must have sunlight
- battery (kWh/kg)	19.50	51.28		180	1999	15	- Must have electric energy storage
- power conditioning electronics	481.06	2.08		250	2000	15	
Thermoelectric (RTG)	5.30	188.68	0.3	133,000 (plus Pu^{238})	1997	30	- Highly survivable against natural radiation and space-based weapon attacks - Heat source degrades 0.8%/yr from Pu^{238} half-life - Converter degrades 0.8%/yr; Cassini
Fuel Cells	51.00	19.61	7	825 (plus fuel)	1981	0.3	- Requires fuel supply
- fuel (Wh/kg)	1550.00	0.65					- Requires fuel storage - Tank weight included - Does not need sunlight - Requires maintenance between flights (Space Shuttle)
Nuclear Thermionic	4.17	239.81	5	5000 (plus fuel)	1987	1.0	- Highly survivable - Cosmos 1818 & 1867; Topaz I

Since the majority of space missions utilize a solar photovoltaic/battery combination to satisfy power requirements and the flight heritage is significant with these systems, the tendency for a survey such as this would be to only focus on some variant of these technologies. However, as other conversion and storage technologies are discovered and selected for missions where the environments are more severe and without sunlight, thereby precluding the use of PV/battery combinations, these technologies will mature to a level where they may be suitable in missions traditionally dominated by the heritage PV/battery combinations. For this reason, technologies traditionally used in deep space missions have been revisited and included in this survey. An overview of the results for each of the technologies is presented below.

III. Survey Results

A. Energy Generation (Harvesting) Technologies

1. Solar (not thermal)

Solar conversion technologies refer to those technologies that directly convert the visible spectrum of energy into electricity and are predominantly based on semiconductor type materials.

Photovoltaics

Photovoltaics, which generate electricity through the formation (interaction with incident photons) and transport of electron-hole charge carriers across an electric field at a semiconductor junction, provide the majority of power for space systems with crystalline cell arrays having the longest history of successful performance. Although state of practice consists of triple junction crystalline cells, such as GaInP$_2$/(In)GaAs/Ge grown on single crystal Ge wafers, with over 30% small area efficiencies and TRLs of 9, thin-film arrays offer higher specific powers (W/kg) and possibly greater radiation tolerance (as in the case of CIGS polycrystalline cells). Today's SOA solar arrays with crystalline solar cells, supported by rigid aluminum honeycomb structures, provide specific powers of 30-100 W/kg for 14-30% efficient (AM0) cells; the cost of the arrays range from \$300-\$1000/W[2] (may be as high as \$2,000/W). Spectrolab recently reported[3] a specific power density of 180 W/kg and 150 W/kg for crystalline UTJ cells (28.3% eff.) at the cell and panel (array on substrate) levels, respectively, (TRL 9) and for crystalline UTJ cells on flexible 2 mil Ge a projected specific power density of 2000 W/kg and 500 W/kg at the cell and panel levels (TRL <6), respectively, (lower stowage volume and array mass results in higher specific power density). Concentrator arrays, utilizing high efficiency solar cells, have reported specific power levels of 378 W/kg (e.g., 8x concentration for Entech's SLA) although when the entire support structure is considered, the specific power is around 50 W/kg.

Flexible polycrystalline (and amorphous) thin-film solar cells, on the other hand, have specific power levels over 1000 W/kg[2,4], depending on the specific support substrate (typically Kapton or stainless steel), for an unsupported array level and when the array support structure is included, specific power densities of ~600 W/kg are possible for cell level efficiencies of 18-20%. A comparison of the leading photovoltaic technologies is presented in Table 2 below; *it is important to note, unless otherwise indicated, that the specific power densities are for cells without the entire array support structure.*

Table 2. BOL Figures of Merit for Photovoltaic solar cells

PV Type (Description)	**Specific Power** (W/kg)	(kg/m^2)	**Efficiency** (%)	**TRL**
Rigid				
(3J) GaInP$_2$/GaAs/Ge	460	0.8	30	>6
(2J) GaInP$_2$/GaAs	320	0.8	22	>6
Cryst. Silicon	750	0.31	17.5	>6
α−Silicon	300	0.31	9	
Flexible				
Polycrystalline CIGS				
SS (1 mil)	700	0.293	10-12	<6
Kapton (2 mil)	1200	0.115	9	3-4
(2J) GaInP/GaAs-*Sharp*	5800	0.058	25	<6
UTJ(2 mil Ge)-*Spectrolab*	2000		28	<6
Organic nanocomposite			2-5	<2

Dye Sensitized

Dye-sensitized solar cells are an alternative to p-n junction photovoltaic devices, wherein the functions of light absorption and charge carrier transport are separated. Light is absorbed by a sensitizer, which is anchored to a wide band gap semiconductor, producing an electron which is then injected into the conduction band of the semiconductor. Although overall solar (AM1.5) to current conversion efficiencies over 10% have been reached[5], the use of a liquid redox electrolyte (for charge neutralization of dye molecules) presents sealing problems in vacuum environments, and with the issue of overall lifetime, this technology would be considered at less than TRL 2. It is important to note that solid state dye-sensitized solar cells have been developed although the efficiencies are less than 5% at this time.

2. *Thermal (solar or radioisotope source)*

Thermal conversion technologies refer to those technologies that convert thermal energy (heat) into electricity. Heat is typically generated either from solar flux or from the decay of radioisotope material; heat can be concentrated and/or re-radiated from various emitter materials. Thermal conversion technologies are typically categorized as either static, with no moving parts, or dynamic.

Dynamic systems are different from static systems in that they include moving parts, such as rotors or pistons and contain a fluid which undergoes state changes to produce thermodynamic work. Many of the space dynamic power system concepts are derived from terrestrial analogs. Brayton technology is commonly used in aircraft auxiliary power units, marine propulsion, and small utility power plants. Stirling technology is used in cryocoolers, residential cogeneration, and solar dish electric systems. The common characteristics of these two mature terrestrial systems are long life, high reliability, and high power density.

Thermoelectric (static)

In combination with a radioisotope power source, NASA has had a long successful track record (over 21 missions) with thermoelectrics (TE) in deep space missions where the solar flux is too low. In the case of thermoelectrics, an electric current is produced in a closed circuit when the junctions of two dissimilar metals are maintained at different temperatures (know as the Seebeck effect) either in a cascaded or segment device configuration to increase overall efficiency. In general, smaller power systems (on the order of 100's of Watts) use thermoelectric methods to extract energy from heat. The following table lists representative TEs with their corresponding figures of merit.

Table 3. Thermoelectric conversion technologies[6,7]

TE Type (Description)	Specific Power		Efficiency	Lifetime	Cost	TRL
	(W/kg)	(kg/m^2)	(%)	(years)	($/W)	
Si-Ge (GPHS-RTG) (1273-573 K)	~5		7-8	>15		>6
PbTe/TAGS (MMRTG, 123W) (Boeing/Teledyne)	3-4		7	>14		5-6
Segmented BiTe, 20W (w/PbTe, PbSnTe, and TAGS)	>5		10-12			3-5
Cascaded (CTC-ARPS, 100W)	8-9		10-11			
Cascaded PbTe/TAGS, 50-100mW) (Superlattice BiTe – Teledyne/RTI)			>8			1-2
Multi-layer, quantum well (Hi-Z Technology, mW range)			25-40			1
Nanostructured Si-Ge (vapor condensed nanowires-MIT)			12-14			1

Thermophotovoltaics (static)

Thermophotovoltaic (TPV) conversion is based on the principle of intermediate conversion of energy into radiation by heating a photon emitter and then photovoltaic conversion of produced radiation in low-bandgap (Eg = 0.5-0.8 eV) photocells. Energy is typically supplied either from radioisotope or solar sources. Efficiency is increased through the development of selective emitters matched to the PV cell spectrum as well as optical filters to return or recycle sub-bandgap photons back to the emitter. Theoretical efficiency limit for a solar TPV is 84.5%

(nearly identical to a multi-stack tandem-type PV cell) and the practical limit should be higher than 30%. TPV is generally used where required power is on the order of 100's of Watts. The TPV technologies and figures of merit are included in the following Table.

Table 4. Comparison of Thermophotovoltaic conversion technologies[6,8,9]

TP Type (Description)	**Specific Power** (W/kg)	(kg/m^2)	**Efficiency** (%)	**Lifetime** (years)	**Cost** ($/W)	**TRL**
InGaAs cells/emitter (Creare, Inc; 85 W)	~15[c]		15-20			3-5
GaSb cells/emitter (EdTek, 80W)	8-14[c]		17-23			3-5
GaSb (w/emitter and filters) (STPV system; 2200-2500K)			25 (no filters) 30 (w/filter)			
InGaAs (filtered grey-body heat source)			20			1
InGaAs MIM on InP (1039 C radiator, 25 C cell)			23.6			<3
InGaAs/InPAs buffer on InP (Emcore, 1000 C emitter)	12		~24			3-5
InGaAs (1350 K, 50 W/500 cm^3) (Sandia(Murray)			25-26 (19% w/Pu	Source)		3-5

Thermionic (static)

Thermionics has been considered as a candidate for space power systems in the regime between a few kilowatts and multi-megawatts. The unique nature of thermionic systems could lead to a lighter, more compact power conversion system. A typical thermionic power system consists of a radiation source (e.g., solar or radioisotope), a thermal energy storage device (e.g., graphite), and the thermionic converter. In its most elementary form, a thermionic converter consists of two metal electrodes separated by a narrow gap. One of the electrodes, called the emitter, is held at a high temperature, typically 1800 to 2000 K. The other electrode, called the collector, is held at a lower temperature, typically 900 to 1000 K. The emitter emits electrons into the gap and the lower temperature collector absorbs them. Electrical power is produced by virtue of the potential difference between the emitter and collector.

In the case of a solar thermionic system, a conceptual system design from General Atomics[10] uses a parabolic reflector (or Fresnel lens) with a cylindrical, inverted multi-cell (CIM) converter. The power density is ~100 W/kg with stowed volume of ~80 W/m^3. In the case of radioisotope thermionic system, systems have been built for high power applications, 20 kW to MW, with 17% efficiencies @ 1700K. The primary issue with this system is the integration of the converter technology into the nuclear reactor core.

AMTEC (static)

Alkali metal thermal to electric converters (AMTECs) are thermally powered electrochemical concentration cells that convert heat energy directly to DC power from any fuel source capable of generating 970 to 1170 K. The converter has no moving parts and efficiencies ranging from 15 to 25 percent depending on operating temperature and specific design features[11]. In operation, an alkali metal such as sodium or potassium ionizes and is driven through an ion-permeable beta-alumina solid electrolyte membrane by a temperature-induced pressure differential. On the cathode at the low pressure side, the alkali metal evaporates, travels as a vapor to a heat sink where it condenses, and then is returned to the high pressure zone by a fine capillary artery or an electromagnetic pump. The charge separation produces electrical power at the anode and cathode surfaces of the ceramic membrane. With its moderate upper operating temperatures and heat sink temperatures from 373 to 623 K, AMTEC is suitable for cogeneration or topping cycle applications.

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[c] NASA goal

Thermodynamically, AMTEC operates as a heat engine. However, in contrast to Stirling, Brayton, and Rankine dynamic cycles, AMTEC systems have no moving parts and are temperature sensitive but relatively insensitive to the choice of heat source. A comparison of representative AMTEC conversion technologies is presented below.

Table 5. Comparison of AMTEC conversion technologies

AMTEC Type	**Specific Power** (W/kg)	(kg/m^2)	**Efficiency** (%)	**Lifetime** (years)	**Cost** ($/W)	**TRL**
Na- AMTEC	5.3		15-25			>6
K - AMTEC	5.8		15-25			>6
With Solar concentrator	5-23		16-20			3-4

Stirling (dynamic)

A Stirling engine uses a heat source to raise the temperature of a sealed working fluid, pressurizing internal cylinders and moving a piston. The heat source can either be radioisotope or solar. Converter (component) alone efficiencies are between 33-37% with specific power densities between 30 and 95 W/kg; system level efficiencies at around 7 W/kg at TRL>6 and >14 year life (source: SunPower website).

In recent tests conducted at Sandia National Laboratories with solar concentrators, the 'Stirling Dish' technology was shown to be almost twice as efficient as other technologies, such as PV. Although the 'Stirling Dish' technology at SNL is terrestrial, there may be attributes of the system that may translate into space applications with comparable results. Although NASA has conducted a trade study for both Stirling and Brayton nuclear power systems for different missions in the power range between 1kW to 10 MW[12], small miniature systems have also been developed for space-borne applications as well. A comparative chart of the different Stirling technologies is presented below.

Table 6. Comparison of Stirling power conversion technologies (system level)

Type (Description)	**Specific Power** (W/kg)	(Temp)	**Efficiency** (%)	**Lifetime** (years)	**TRL**
Stirling Radioisotope Generator (SRG, 112 W)	7.28 9.9[d]	973-373K 1273-573K	 13.8	>14	>6
Hybrid SiGe-STE/SRG	10.7	1273-373K	16		>6

Brayton(dynamic)

Similar to the Stirling engine in that it uses a heat source to raise the temperature of a sealed working fluid, the Brayton engine uses a turbine instead of a piston for actuation. Brayton engines have been used in NASA's high power systems although there has been development of miniature turbo-Brayton technologies for low-power applications (i.e., ~100 W). Creare reports a turbo-Brayton Power System (TBPS) with a 25-36% efficiency (38% Carnot efficiency) with a unit power density (component level) of 41.7 W/kg and system power density of 9-13 W/kg for flight units (>TRL 6)[12].

Thermoacoustic (dynamic)

Similar to the Stirling engine, a thermoacoustic-Stirling engine converts heat into acoustic power which is then converted into mechanical power by the motion of a flexible diaphragm. In turn, mechanical power is converted into electrical power with a piezoelectric alternator. A small 13 liter system at Los Alamos was shown to produce 4 kW of electricity with 25% conversion efficiency with power densities on the order of 6-8 kg/kW (TRL ~2)[7].

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[d] Note: Next generation system-projected values assuming 50% Carnot efficiency and converter alone power density of 90 W/kg.

3. *Radioisotope (α,β)*

Radioisotopes in space are primarily used in thermal generators (RTGs) wherein the radioisotope is used to generate heat which is then converted to electricity (refer to previous section). Radioisotopes, however, can be directly converted into electricity via 'betavoltaics', in which the energy from a beta (or alpha) particle creates an electron-hole pair in a semiconductor which is then swept across a p/n junction to create electricity, similar to a solar cell. While devices converting radioisotopes sources via the photovoltaic effect have existed since they were proposed in 1954[13], the implementation of these devices has not been widespread due to low power densities (low incident particle fluxes) and degradation of the lattice structure of the p/n semiconductor material(s). A number of innovations have occurred over the last few years in order to overcome these limitations; i.e., more radiation tolerant, wider band gap semiconducting materials, incorporation of radiation transducers, such as mediating fluorescent gases, and improved 3-D morphologies (or lateral junction *nipi* devices) to increase collection efficiency.

Unlike traditional PV cells where the system level power densities are fairly well established, the figures of merit for betavoltaics are more ambiguous (nebulous) as the technology is less mature. A comparative of the different 'betavoltaic' technologies is presented below in Table 7.

Table 7 - Comparison of 'Betavoltaic' energy conversion technologies [14,15,16,17]

Type (Description)	**Specific Power**		**Efficiency**	**Lifetime**	**Cost**	**TRL**
	(W/kg)	(kg/m^2)	(%)	(years)	($/W)	
β-source						
GaN			>18[e]			1-2
BetaBat (Tritium source in 3-D Si)			2.5[f]			3-4
Qynergy (β-particles from Pr_{147} and Kr_{85} source)			11			3-4
α-source						
InGaP (Am_{241}) (ZnS:Ag phosphor mediator)	5 (mW/cm2)	3 (g/5mW)	6			
AlN/C (Pu_{238}) (fluorescent gas)	18-32		9-20 (diamond)			

In a habitat power study by NASA[18] (50 kW), both alpha and beta voltaic (tritium in amorphous silicon and tritium-phosphor in Si converter) were effectively eliminated from the study as a result of poor mass scaling above the mW level. Similarly, to be competitive with thermoelectric devices (RTG applications), they must achieve an efficiency above 20%[19].

4. *Power Beaming (Rectenna)*

Just as energy in the UV/vis/IR region of the electromagnetic spectrum is converted into electricity, energy in the lower energy, longer wavelength, region of the electromagnetic spectrum, i.e., micro and millimeter wave can also be converted into electricity at high efficiencies using well established rectenna (antenna with rectifying diodes) technology. Traditionally, this technology has been used in the context of power beaming, wherein power (either microwave or laser) is beamed from one location to the other; i.e., from Earth to a geosynchronous orbit, with a well-behaved polarization signature. Although issues with transmitting through (interacting with) the atmosphere affect the efficiency of the technology, and have been addressed to some degree, the efficacy of this type of system for powering satellites is poor. In the NASA habitat study referenced above, power beaming technologies were effectively eliminated based on the high mass requirements and insufficient TRL for both RF and laser diode systems. A comparison study of laser versus microwave power beaming is presented in Table 8.

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[e] Calculated

[f] 8% PV power-conversion efficiency in the pore channels; 2.5% overall

Table 8. Laser vs. Microwave Power Beaming[20]

Type	Operating Wavelength	Transmitter System	Transmitter Area	Receiver System	Overall System Eff.	High altitude operation	Development level
Laser	0.84 microns	Free-Electron laser/ deformable mirror	12 m diameter	Tuned solar cells	2%	Preferred	Under construction
Microwave	3.2 mm (94 GHz)	Phased Array	1 km diameter	Rectennas	0.05%	Preferred	Design stage

However, although the concept of power beaming, as discussed above, may not be appropriate for space applications, the technology of direct conversion of microwaves into electricity is an effective energy harvesting method in that it has been shown to have a conversion efficiency greater than 75% in diode rectification antenna systems. Similarly, in previous work at ITN, using a patented grid array design for collecting elliptically polarized microwave energy sources, the viability of collecting non-traditional sources of energy, such as parasitic side-lobe energy from a primary communication beam, was demonstrated in the 10 GHz range at a conversion efficiency of greater than 65% using off-the-shelf components.

B. Energy Storage

Although various energy generation methods were presented in the previous section, even the best of energy generation systems will still require some type of power storage function, if nothing other than to provide the option of delivering power of a given magnitude at a specific time. In this section, both conventional types of energy storage methods, i.e., electrochemical and electromagnetic, as well as other 'next generation' methods, are reviewed. .

As a first-order means for comparison and reference, a Ragone plot is presented (Fig. 4) in order to compare the energy storage and power handling capacity of typical energy storage methods. A review (Table 9) is also included from a 1997 Army study for the soldier in the field[21]. Recent developments in storage technology have changed the values in the figure and table, and therefore, an updated overview of each of the technologies is discussed in more detail below.

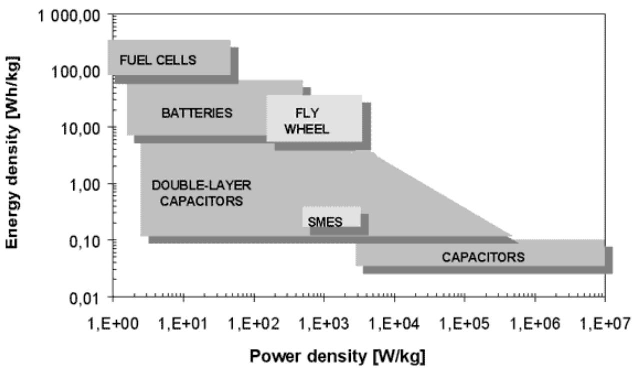

Figure 4. Energy Density versus Power Density (Ragone plot) for various energy storage technologies

1. *Electrochemical*

Electrochemical systems include batteries (primary and secondary), fuel cells, and capacitors. In general, rechargeable batteries have been the technology of choice in a combined energy generation/storage system for earth orbits. Traditionally, nickel-hydrogen (Ni-H_2) batteries have been used almost exclusively in space for power storage, although the dominant technologies in terrestrial applications, Lithium Ion and Nickel Metal Hydride, are being qualified for space. Depending on the mission power requirements, there may be applications where primary batteries may be appropriate, on an energy density basis, and therefore primary batteries have also been included in the survey.

Table 9[g]. Comparison of Soldier Power/Energy Sources for 100-W Avg. Power Missions of 24 and 72 Hrs[21]

Type of Technology	Mission Length (hr)	System Mass (kg)	Power (W)	Total Energy (Wh)	Specific Energy (Wh/kg)	TRL
IC (JP-8)	24	2.70	100	2,400	889	4
Stirling (JP-8)	24	4.00	100	2,400	600	2
SOFC (JP-8)	24	4.24	150	3,600	849	4
PEM/H_2 6%	24	6.21	100	2,400	386	7
Li/$(CF)_x$ (SOA)	24	7.69	100	2,400	614	8
Li/MnO_2 (SOA)	24	8.57	100	2,400	280	8
DMFC	24	11.40	150	3,600	316	6
Li/MnO_2 (LW)	24	12.31	100	2,400	195	9
Li ion (SOA)	24	14.12	100	2,400	170	8
Li ion (LW)	24	16.55	100	2,400	145	9
IC (JP-8)	72	5.70	100	7,200	1,263	4
Stirling (JP-8)	72	6.00	100	7,200	1,200	2
SOFC (JP-8)	72	7.42	150	10,800	1,456	4
PEM/H_2 6%	72	10.93	100	7,200	659	7
SOA Li/$(CF)_x$	72	11.70	100	7,200	614	8
DMFC	72	18.60	150	10,800	581	6
Li/MnO_2 (SOA)	72	25.71	100	7,200	280	8
Li/MnO_2 (LW)	72	36.92	100	7,200	195	9
Li ion (SOA)	72	42.35	100	7,200	170	8
Li ion (LW)	72	49.66	100	7,200	145	9

Primary Batteries

Primary batteries are a ‘one-time use’ option with long shelf life and robust, consistent operation with no voltage delays. In the case of lithium cell chemistry, pure lithium can be used as the anode with high energy density and therefore, primarily lithium cell chemistry was considered for this study. Energy densities of typical primary cells are presented below in Table 10.

Lithium sulfur dioxide- With a cathode of porous carbon and sulfur dioxide (or thionyl chloride), electrolyte of acetronitrile and lithium bromide salt, the lithium sulfur dioxide chemistry has high energy content, excellent shelf life, high-rate capability, with good low temperature performance (requires pressurization however). Current energy

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[g] Table is sorted by system mass. TRL, technology readiness level; JP-8, jet propellant 8; IC, internal combustion; SOFC, solid oxide fuel cell; PEM, proton exchange membrane; DMFC, direct methanol fuel cell; LW, Land Warrior.

density is around 240-280 Wh/kg for SO_2 cathode and 390 Wh/kg for $SOCl_2$ cathode with an open circuit voltage of almost 3V (>TRL 6)[22].

Lithium/Polycarbon Monofluoride (LiCFx)-The cathode for this cell is carbon monofluoride with a lithum tetrfluorobate salt/propylene electrolyte. Current energy density is around 250 Wh/kg with an open circuit voltage around 3 V and 7 year shelf life (>TRL 6); recent laboratory developments have yielded energy densities of 600 Wh/kg[22].

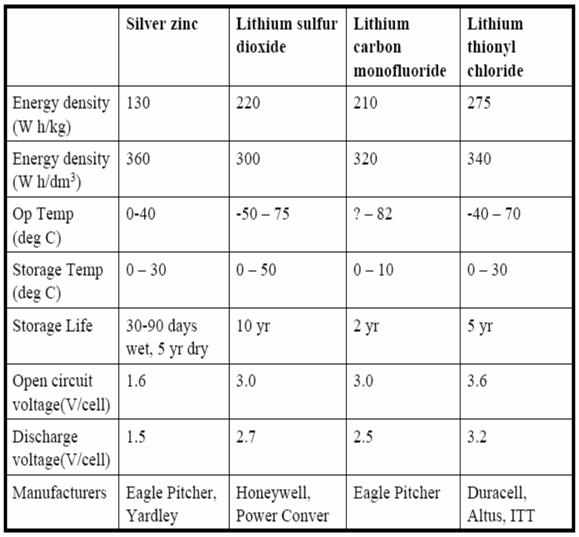
Lithium-Air-Lithium-air batteries consist of lithium anodes electrochemically coupled to atmospheric oxygen (unlimited source for terrestrial applications) through an air cathode with a non-aqueous electrolyte. Theoretical specific energy is 5.2 kWh/kg (including weight of oxygen) with a flat discharge profile and long storage life. Practical energy densities have been increased by improving the carbon-based, air cathode structure and a current practical energy density (although not demonstrated for space) would be around 1100 Wh/kg (including packaging (TRL 4-5)[22]).

Secondary Batteries

Although secondary, or 'rechargeable' batteries have traditionally had a lower energy density than primary batteries, they can be recharged and therefore work well in a power generation/storage system. For space applications, the nickel-hydrogen battery has the longest flight heritage and consists of a hydrogen-nickel chemistry in a pressurized canister. In an Earth orbit[23], batteries are charged during insolation and discharged during eclipse and are typically designed to operate at a 35% depth of discharge (DOD) maximum during normal operation (Eagle Picher Industries cells have a design lifetime of 6.5 years) at a temperature of 5 ^{o}C +/- 5. Specific energy density is ~54 Wh/kg for Independent (IPV), Common (CPV), and Single Pressure Vessel (SPV) categories.

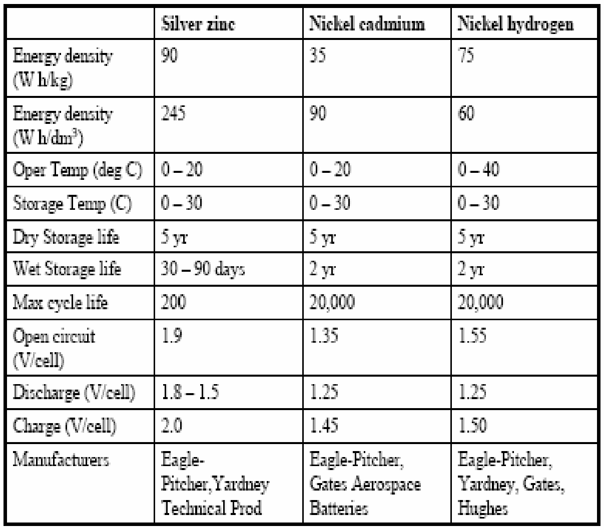
Alternative, next generation, battery types are discussed below and a comparative table of traditional non-lithium, terrestrial battery types are presented in Table 11 below. It is important to note that when comparing the energy or power density of different secondary battery types for space, the depth of discharge (DOD) must be considered in the calculation. For example, in Table 11 and in the discussions below, the energy density is based on a 100% DOD and in actual practice, the DOD may be less, depending on how long the battery needs to operate.

Table 10. Primary Battery Types



	Silver zinc	Lithium sulfur dioxide	Lithium carbon monofluoride	Lithium thionyl chloride
Energy density (W h/kg)	130	220	210	275
Energy density (W h/dm^3)	360	300	320	340
Op Temp (deg C)	0-40	-50 – 75	? – 82	-40 – 70
Storage Temp (deg C)	0 – 30	0 – 50	0 – 10	0 – 30
Storage Life	30-90 days wet, 5 yr dry	10 yr	2 yr	5 yr
Open circuit voltage(V/cell)	1.6	3.0	3.0	3.6
Discharge voltage(V/cell)	1.5	2.7	2.5	3.2
Manufacturers	Eagle Pitcher, Yardley	Honeywell, Power Conver	Eagle Pitcher	Duracell, Altus, ITT

Table 11. Conventional Secondary Battery Types



	Silver zinc	Nickel cadmium	Nickel hydrogen
Energy density (W h/kg)	90	35	75
Energy density (W h/dm^3)	245	90	60
Oper Temp (deg C)	0 – 20	0 – 20	0 – 40
Storage Temp (C)	0 – 30	0 – 30	0 – 30
Dry Storage life	5 yr	5 yr	5 yr
Wet Storage life	30 – 90 days	2 yr	2 yr
Max cycle life	200	20,000	20,000
Open circuit (V/cell)	1.9	1.35	1.55
Discharge (V/cell)	1.8 – 1.5	1.25	1.25
Charge (V/cell)	2.0	1.45	1.50
Manufacturers	Eagle-Pitcher,Yardney Technical Prod	Eagle-Pitcher, Gates Aerospace Batteries	Eagle-Pitcher, Yardney, Gates, Hughes

Lithium Ion- The cathode for this type of cell is lithium metal oxide with a layered intercalating graphite anode and $LiPF_6$, $LiBF_4$, or vinyl carbonate electrolyte. The current energy density for lithium ion is ~170 Wh/kg @ 3.7 Volts with low maintenance, although these cells require circuit protection. The maximum discharge is limited to between 1C and 2C, and there are issues with ageing. For example, Lithion reports the following information (Mars Lander mission) of a lithium ion cell on their website:

- Energy density: 358 Wh/L; Specific energy: 145 Wh/kg

- Operating life: 2100 deep cycles; Rapid recharge capability: C rate

- Discharge capability: Continuous 10C rate, Pulse 50C rate
- Broad temperature capability: -40° C to +65° C

Lithion and Quallion report recent energy densities of 200-220 Wh/kg and 150 Wh/kg, respectively[3]. To obtain the high cycle lifetimes required for space (i.e., >60,000), the conventional SOA lithium ion cells are discharged between 20-40% of full depth of discharge and thereby reducing the actual energy density of the battery. In fact, by the time a lithium ion cell of ~150 Wh/kg is fully integrated into a spacecraft system, the energy density can drop to around 6-8 Wh/kg; hence, *a power storage system that can be directly integrated into the final spacecraft system, with minimal loss in energy density with system integration, can have a dramatic impact on the overall weight of the spacecraft.*

Solid State Lithium-Although similar to a lithium ion battery with a lithium oxide intercalating cathode, a solid state lithium battery differs from a traditional lithium ion battery in that it utilizes a lithium anode and an all solid state inorganic electrolyte, such as the patented LiPON from Oak Ridge National Laboratory. Use of pure lithium in a stable, reversible cell chemistry, such as the solid state configuration, enables a higher energy density, longer cycle life (>10,000 at full depth of discharge), and simpler integration without the need for conventional packaging/encapsulation. Depending on the supporting substrate, the energy density of the solid state battery will be on the order of 250 Wh/kg @ 3.7 V.

Lithium Ion Polymer-A lithium polymer battery uses a gelatinous electrolyte rather than a liquid and stores less energy per kilogram than lithium ion although the cells can be manufactured in thin, conformable geometries. Internal resistance is high and therefore, cannot deliver high current bursts. Ultralife reports (www.ultralifebatteries.com) an energy density of 150 Wh/kg @ 3.7 V for their lithium ion polymer battery. It is important to note that the energy densities reported are for conventional terrestrial packaging and that higher energy densities are possible with appropriate novel packaging in space (i.e., on the order of 220 Wh/kg).

Nickel Metal Hydride-The NiMH is a sealed cell that is a cross between a NiCd and a NiH_2 cell; i.e., a rare earth ($LaNi_5$) or nickel alloy anode with a nickel oxyhydroxide cathode and KOH electrolyte. NiMH provide ~100 Wh/kg @ 1.2 V and provide good power density (Ovonics reports up to 70 Wh/kg with 1000 cycles) although they suffer from high self discharge.

Reserve Batteries

This type of battery is used in applications requiring rapid activation and high power in a comparatively short time. In a reserve cell, the electrolyte is kept separate from the rest of the battery and upon activation, comes into contact with the electrode materials; hence, reserve batteries can have greater than a 20 year shelf life.

A novel reserve battery architecture, based on superhydrophobic nanostructured electrode materials (such as silicon), has been developed by mPhase and Lucent Technolgies in order to separate the liquid electrolyte from the active electrode materials. Electro-wetting promotes electrolyte penetration into the electrode space to initiate the electrochemical reaction. This approach provides a simple activation mechanism.

Lithium anode-These provide significant energy over other reserve batteries (similar energy density to lithium primary cells). An organic or non-aqueous inorganic electrolyte is physically separated from the anode and cathode until activation, resulting in shelf life of 10 years.

Thermal Batteries

Thermal batteries employ inorganic salt electrolytes (typically lithium chloride and potassium chloride that is non-conducting as a solid) and have excellent shelf-life. Activation occurs when the electrolyte is melted and becomes active. Activated life is typically several minutes although depending on the level of insulation and the availability of anode/cathode materials (typically lithium silicon/iron disulfide), can be extended to over a few hours (although time for activation is less than a few seconds). A heat pellet is used to activate the cell in the 500-700 C range. The energy density for a thermal battery is similar to a primary cell chemistry.

Fuel Cells

A fuel cell is an electrochemical “cell” that combines a fuel and an oxidizing agent, and converts the chemical energy directly into electrical power. Fuel cells can be considered as primary (i.e., tanks of fuel and oxidant which are gradually discharged and not replenished) or secondary (hydrogen and oxygen as reactants with the use of external power to electrolyze the water to ‘regenerate’ the hydrogen and oxygen). Traditionally, NASA has used Proton Exchange Membrane Fuel Cells (PEMFC) and Alkaline Fuel Cell (AFC) technology and currently NASA is funding the development of only PEMFC and Direct Methanol Fuel Cell (DMFC) technologies for space applications (ERAST and LEAP programs with 4.5 to 5 kWe delivered power[24]). With higher reported efficiencies, good energy density (1 kW/kg) and more versatility to fuel type (i.e., direct use of hydrocarbon fuels) than PEM, solid oxide fuel cells (SOFC) are a viable alternative although start-up times are slower and cells operate at higher temperatures (>600 ^{o}C). An alternative peroxide based fuel cell design, using novel fuel and oxidizer in aqueous form, is reported to have an energy density on the order of 1000 Wh/kg and efficiency on the order of 75% at 30 ^{o}C.

Improvements in fuel cell designs as well as improvements in lightweight high-pressure gas storage tank technology make fuel cell technology worth a look to see if fuel cells can play a more expanded role in space missions. A preliminary study at NASA Glenn Research center indicates that fuel cell systems have the potential for energy densities of >500 Whr/kg, >500 W/kg, >400 Whr/liter, and >200 W/liter. As a comparison, DOE’s 2010 goals for auxiliary (PEM-based) fuel cell power systems (3-30 kW) are 150 W/kg specific power and 170 W/l power density; at the stack level, the 2010 DOE goals are for specific power levels of 2 kW/kg and $30/kW (PEM-based system).

The hydrogen-oxygen regenerative fuel cell system (RFCS) has a specific energy storage capability (packaged) of between 300-1000Wh/kg according to a NASA study and therefore can provide higher specific energies than any advanced battery system. RFCS systems are attractive in applications, such as aerospace, that are mass sensitive. A table of the energy density of various batteries and fuels is presented in Table 12 below and clearly shows the potential for higher energy densities with direct conversion of fuels. However, it is important to note that once packaging, handling, and cost metrics are considered, the high energy density fuels are less attractive. Nevertheless, an RFCS could potentially have the highest storage capacity and lowest weight of any non-nuclear device and due to a limited round trip efficiency of 75% for RTE devices (irreversible heat generation), the 50-60% RTE and high energy density for a RFCS technology would make this an attractive technology. The real question for any PEM or SOFC fuel cell system will be the TRL for space as most of the reported results for this technology would be less than TRL 6.

Based on terrestrial applications, the current cost estimates for the different types of fuel cell types are listed below:

- Proton Exchange Membrane (PEM), 1-10 kW - $5,000/kW
- Phosphoric Acid, 200-1000 kW - $3,500/kW
- Solid Oxide, 1-250 kW, $10,000-20,000/kW

A comparison of different power generation/storage technologies along with TRL ratings, based on a NASA study for Lunar power options[18] (human rover applications), is presented below in Table 13. It is important to note that although the specific power for fuel cells appear higher than battery and Stirling technologies, the specific power levels are on the order of 12-25 W/kg (at a system level).

Table 12. Energy density of various batteries and fuels, listed in order of increasing energy density

Type of Fuel	**Energy Density** (Whr/kg)	**Comments**
BB-2590	81	Secondary
BA-5590	150	Primary
BA-5390	235	Primary
BA-8180	345	Primary Zn-Air battery, large unit
Compressed Hydrogen	500-1000	5000 psig, value includes container weight
Sodium Borohydride	3600	[$NaBH_4$ + $2H_2O$] weight
Methanol	5500	Based on lower heating value of fuel
Most Liquid Hydrocarbons	~12,400	Based on lower heating value of fuel
Hydrogen Gas	33,200	Unpackaged
Nuclear Material	2,800,000	Raw Power

Table 13. Comparison of different power generation/storage technologies based on a NASA study for Lunar power options[18]

Type (Description)	Mass (kg/kW)	Specific Volume (m^3/kW)	Lifetime (years)	TRL
Radioisotope/ Stirling	100	2.2		4
Liquid Li Ion Battery	118	n/a	0.04	5
2nd PEM RFC	82	1.0	0.22	4
Primary PEM PC	40	1.0	0.14	4

Capacitors (Super/Ultra)

Supercapacitors, or Ultracapacitors, are electrochemical double layer capacitors. Though similar to batteries in construction as storage devices, supercapacitors involve only electrostatic phenomenon (i.e., non-faradaic processes without redox reactions). The power density of supercapacitors is higher than batteries because there are no chemical reactions during charging and discharging and similarly, with a reduced time constant for loading and unloading, the lifetimes are much greater than batteries. The specific energy density of supercapacitors is on the order of 2.5-7 Wh/kg (Japan Space Agency reports a 40 Wh/kg supercap although not available for purchase; <6 TRL) with specific peak power on the order of 3-5 kW/kg @ 2.5 V (TRL >6)[3].

Efficiencies of supercapacitors are on the order of 85-98%, can operate in a wide temperature range and humidity, and can store charge for more than 10 years[25]. In double layer capacitors, the amount of energy stored is a function of the available electrode surface, the size of the ions, and the level of the electrolyte decomposition voltage and therefore recent approaches to improving the performance of supercapacitors has been in the improvement in the surface area of the electrodes. For example, in recent work at MIT’s Laboratory for Electromagnetic and Electronic Systems (LEES), the surface area of the electrodes have been increased by using vertically aligned, single-walled carbon nanotubes with a regular array to create a more effective charge storage geometry (potentially on the order of electrochemical systems, such as batteries).

2. *Mechanical*

Flywheel

Flywheels store kinetic energy. A rotating mass driven by a motor with a variable speed drive system is the most common configuration. Though flywheels have been used for centuries, recent advances in topology and materials have significantly increased the amount of energy that they store. Flywheels can perform simultaneous energy storage and attitude control functions with gimbaled wheels and thereby improve the system level energy density metric with dual functionality.

Flywheels naturally produce high power in a fairly small space essentially on demand. They charge and discharge rapidly. They exhibit little sensitivity to operating temperature or discharge patterns. They require less maintenance than lead acid batteries, but more than lithium ion or nickel metal hydride batteries. Their commercial capacity range is from 500 Whr to 500 kWhr. Specific energy and power densities are on the order of 50-100 Whr/kg and 900-10,000 W/kg, respectively, and are designed to discharge in under a minute with around 90% DOD. For example, Beacon Power reports, for a 7.2 kWh system, a 102 Whr/kg specific energy density and capability to discharge 5 kWhr in ~10 minutes[3].

Recent advances in composite materials technology have produced flywheels that rotate above 100,000 rpm with tip speeds in excess of 1000 meters/second[26]. Magnetic bearings and vacuum enclosures reduce losses to about 0.1% of stored energy per day. Advances in variable speed drive control technology enable counter-rotating flywheels to greatly mitigate the gyroscopic effects. Enclosures must still be strong and therefore increases weight and cost. Hence, the primary issue of flywheel systems is the overall mass. For comparison, NASA Glenn is projecting the following flywheel demonstration goals:

- System specific energy (usable)>50 WHr/kg (within 5 years), >200 WHr/kg long term,
- Cycle life > 75,000,
- Round trip efficiency > 90%,
- System cost reductions > 25%,

Finally, in contrast to batteries, the system level specific energy density for flywheels is within 60% of the component level specific energy density and in combination with the dual energy storage/attitude control functionality, provides mass savings at a systems level.

3. Magnetic

Superconducting magnetic energy storage (SMES)

Superconducting magnetic energy storage uses a low-temperature coil to store energy inductively. At cryogenic temperatures, under a range of current and magnetic flux density, some materials lose all electrical resistance. A current will flow in these superconducting materials without any loss of energy. In SMES systems, this current is made to circulate in a superconducting coil, storing energy in a magnetic field. Control of this current is normally by means of a power electronic converter. Charge/discharge efficiency is typically greater than 95% and energy can be delivered within a microsecond of a request. In SMES, coil components and refrigeration capacity dictate energy density; the design of the power converter dominates power density.

To become competitive for energy storage in mobile electric power systems, SMES will require a breakthrough in superconducting materials. SMES are typically quite heavy and expensive, require handling of a cryo coolant, and the energy content is small and short-lived. Low-temperature SMES cooled by liquid helium is commercially available today, and "high temperature" (less cold) SMES cooled by liquid nitrogen is in development. SMES are typically used for stabilizing large-scale transmission systems at power levels above 100 MW.

4. Thermal (phase change)

In terrestrial applications, phase-change materials are salts developed to undergo liquid/solid phase changes at temperatures as high as 47°F (8°C), and to store and release large amounts of energy during the phase change. Stored in hermetically sealed plastic containers, phase-change materials change to solids as they release heat to chilled water that flows around them. At these temperatures, chillers can operate more efficiently than at the low temperatures required by ice storage systems. Phase-change materials also store about three times more Btu per pound (Joules per kilogram) than a typical chilled-water storage system.

Spacecraft solar dynamic power systems typically use high-temperature phase-change materials to efficiently store thermal energy for heat engine operation in orbital eclipse periods. Lithium fluoride salts are particularly well suited for this application because of their high heat of fusion, long-term stability, and appropriate melting point. Considerable attention has been focused on the development of thermal energy storage (TES) canisters that employ either pure lithium fluoride (LiF), with a melting point of 1121 K, or eutectic composition lithium-fluoride/calcium-difluoride ($LiF-20CaF_2$), with a 1040 K melting point, as the phase-change material. Primary goals of TES canister development include maximizing the phase-change material melt fraction, minimizing the canister mass per unit of energy storage, and maximizing the phase-change material thermal charge/discharge rates within the limits posed by the container structure.

IV. Conclusion

A survey of existing and next generation space power technologies, both generation (source) and storage, for Responsive Space Missions was to assess future power technologies. Although it will be difficult to displace the current advantages of a solar photovoltaic/battery combination in terms of specific power and energy density, respectively, for earth orbits, as mission lifetimes are shortened and power requirements reduced (or even increased) for example, other power options, such as radioisotope, thermal photovoltaics, flywheels, and primary batteries become attractive as well as emerging hybrid and multifunctional power options, such as flexible photovoltaics, all solid state batteries and supercaps, and parasitic rectenna technologies. This latter feature of multi-functionality, i.e., integrated structure-power, thermal management – power, flexible electronics-power, and the like, are becoming more viable with recent developments in nanometer-scale fabrication and materials development and their influence on specific energy and power density.

Acknowledgments

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References

[1] National Research Council, Thermionics Quo Vadis? An Assessment of the DTRA's Advanced Thermionics Research and Development Program, (2001), 84p.

[2] National Research Council, Laying the Foundation for Space Solar Power: An Assessment of NASA's Space Solar Power Investment Strategy, (2001), 94p.

[3] 24th Annual Space Power Workshop (2006), Manhatten Beach, CA.

[4] D. Hoffman, "A Parametric Assessment of the Mission Applicability of Thin-Film Solar Arrays", NASA/TM-2002-211720.

[5] M. Gratzel, "Dye-sensitized Solar Cells", J. of Photochemistry and Photobiology C: Photochemistry Reviews, 4 (2003), p.145.

[6] W. Wang, "Advanced Radioisotope Power Conversion Technology Research and Development", NASA/TM-2004-213352.

[7] DARPA Direct Energy Conversion Workshop, Coronado, CA, (2004).

[8] C. Murray et al, "TPV Converter Design for Radioisotope Power Systems", American Institute of Physics, (2004).

[9] U. Khvostikov et al, "Photovoltaic Cells for Solar Powered TPV Systems", IEEE PV Specialists Conference (2005).

[10] U. Streckert et al, "Conceptual Design of High Power Advanced Low Mass (HPALM) Solar Thermionic Power System", Space Technology and Applications International Forum-AIP Conference Proceedings, 608, (2002).

[11] T. Hendricks et al, "High Performance Radial AMTEC Cell Design for Ultra-High Power Solar AMTE Systems", J. of Solar Energy Engineering, 122, (2), p. 49.

[12] L. Mason, "A Comparison of Brayton and Stirling Space Nuclear Power Systems for Power Levels from 1 kW to 10 kW", NASA/TM-2001-210593.

[13] P. Rappaport, "The Electron-Voltaic Effect in p-n Junctions Induced by Beta-Particle Bombardment", Phys. Rev. 93, 1954, p. 246.

[14] C. Honsberg, W. Doolittle, M. Allen, C. Wang, "GaN Betovoltaic Energy Converters", IEEE Specialists Conference (2005).

[15] S. Bailey, D. Wilt, S. Castro, C.Cress, and R.Raffaelle, "Photovoltaic Development for Alpha Voltaic Batteries", IEEE Specialist Conference (2005).

[16] E. Steinfeldts, T. Ghosh, M. Prelas, R. Tompson, S. Loyalka, "Development of Radioisotope Energy Conversion Systems – Efficient Radioisotopic Power", Proc. Of ICAPP '03, (2003), p. 1.

[17] W. Sun, N.Kherani, K. Hirschman, L.Gadeken, P.Fauchet, "A Three Dimensional Porous Silicon p-n Diode for Betaviltaics and Photovoltaics", Adv. Mat., 17, (10), p. 1230.

[18] T. Kerslake, "Electric Power System Technology Options for Lunar Surface Missions", NASA/TM-2005-213629.

[19] G. Jeffrey Snyder and T.S. Ursell, "Thermoelectric Efficiency and Compatibility", Phys. Rev. Lett. 91, 148301, (2003).

[20] NASA Institute for Advanced Concepts (NIAC) report.

[21] Committee of Soldier Power/Energy Systems, National Research Council, "Meeting the Energy Needs of Future Warriors", (2004), 136p.

[22] DoD Power Source Systems Workshop,, "Roadmap and Strategic Investment Plan", Next Generation Manufacturing Technology Initiative, 24 Feb. 2006.

[23] F. Cohen and P. Dalton, "Update on International Space Station Nickel-Hydrogen Battery On-orbit Performance" , NASA TM-2003-212542.

[24] C. Garcia, B. Chang, D. Johnson, D. Bents, and V.Scullin, "Round Trip Energy Efficiency of NASA Glenn Regenerative Fuel Cell System", NASA/TM-2006-214054.

[25] A. Schneuwly, "Properties and Applications of Supercapacitors from the State-of-Art to Future Trends", Proc. PCIM 2000.

[26] K. McLallin, "The NASA Flywheel Battery Project", 2004 NASA Environment and Energy Conference, May 26, 2004.