Energy Storage Technologies for Planetary Science and Astrobiology Missions

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1.0 Introduction

Energy storage devices are key components of spacecraft power system, and provide power by themselves, or function as energy storage together with a photovoltaic or nuclear primary power source. Various types of energy storage (ES) technologies have ably supported NASA missions in the past, including primary batteries, rechargeable batteries, capacitors and fuel cells.¹ Often, the capability and longevity of a space mission is dictated by the performance characteristics of the ES device, whether it is its specific energy, energy density or ability to survive and operate in the challenging environments relevant to the mission. In other words, advanced ES technologies will significantly enhance planetary missions or even enable NASA to venture into new environments yet to be explored. Reducing the mass and volume of the ES device is a perpetual goal to enable or expand mission capabilities, as identified in the previous decadal survey. The power system typically takes up a good portion of the spacecraft's mass and volume, and improved specific energy and energy density of the ES device will increase the scientific instrument payload, enhance science and decrease launch costs.

The purpose of this paper is to identify energy storage technologies that will enable or enhance the capabilities of the next decadal planetary missions.

Many of the next decadal planetary science and astrobiology missions cannot be implemented with the state of art ES technologies. More advancements in ES technologies are required to enable missions with challenging environments and also to enhance the capabilities, with long mission operating lifetime and increased payload. In general, the ability to operate in these environments with enhanced specific energy or power will enable new missions that were previously considered unattainable. NASA is planning to undertake several exciting planetary science and astrobiology mission concept studies in the next decade, including those listed below and grouped into distinct categories:

- Outer Planetary Missions: i) A large strategic-class study for the exploration of the Ice Giants to either Uranus or the Neptune-Triton system, ii) Flagship concepts for astrobiology at Enceladus,
- Inner Planetary Missions: i) Venus flagship mission study, ii) Mercury lander,
- Mars Missions: i) Mars orbiter for resources, Ices, and Environments (MORIE), ii) MOSAIC: Mars orbiters for surface-atmosphere-ionosphere connections,
- Lunar Missions: i) Intrepid planetary mission concept (Long-life Lunar Rover), ii) Developing the lunar geophysical network mission,
- Miscellaneous Missions: i) Habitability of Dwarf Planet Ceres ii) Pluto orbiter and Kuiper Belt exploration mission and ii) In-situ Geochronology for the next decade.

For these missions the energy storage systems are required to have i) long calendar, operational and cycle lives for outer planetary missions, ii) resilience to either high temperatures on Venus and Mercury, or low temperatures on Mars and Ocean Worlds, iii) ability to tolerate high intensity radiation for Jovian missions and iv) high energy densities for future landers, rovers and probes.

These missions could be categorized as: i) orbiters or fly-bys, ii) aerial vehicles including probes, iii) surface missions (landers and rovers), and sample return missions. Orbital and fly-by missions require rechargeable ES systems (batteries and capacitors) with long cycle life and calendar life, e.g., capacitors in Voyager, Galileo and Cassini or Ni-H₂ or Li-ion batteries for Mars orbiters, Juno and Europa Clipper. Planetary landers and rovers require primary and

rechargeable batteries with high specific energy, and an ability to operate over wide temperatures, e.g., Li-ion batteries in Mars Exploration, Curiosity and Perseverance rovers, or primary batteries in Mars Sojourner and future Europa lander. Sample return missions need primary batteries with long shelf life, e.g., Li-SO₂ in Stardust and Genesis. Table-1 lists the performance targets for these missions.

Table 1: Types of missions and their energy storage performance targets

Planetary science missions have key performance needs that are similar to the commercial and defense applications, with emphasis on reducing mass and volume of the energy storage systems to increase payload, and improving cycle and calendar life to enable long-life missions. NASA may take advantage of the technology developments being supported by the Department of Energy, Department of Defense and the industry for commercial applications, but will need to adapt and validate them for the missions. Additionally, there are unique technologies for the extreme environments, as in some future missions, which will need to be exclusively developed by NASA. Below is a brief description of the capabilities State of Art (SOA) ES systems and the projected performance from future technologies of relevance to NASA's decadal missions.

2.0 Aerospace Energy Storage Technologies

2.1 State of Art (SOA) Rechargeable Batteries

Rechargeable batteries are being used in solar-powered missions to provide electrical power during eclipse periods and for load-leveling. Likewise, they are also being used in conjunction with radioisotope power systems, e.g., Mars Curiosity and Mars 2020 rover. Li-ion batteries are the baseline batteries in almost all the current and near-term NASA missions, aided by their higher specific energy and energy density compared to the previous aqueous chemistries, e.g., nickel-hydrogen. Cells for the Li-ion batteries could be commercial off-the shelf (COTS), pioneered by Sony HC 18650 cells, and now available from LG Chem, Samsung or Panasonic, or the large-format custom cells, i.e., flat-plate or wound prismatic cells manufactured by Yardney Technical Products (EaglePicher Technologies) or GS Yuasa, or cylindrical cells developed by SAFT. By virtue of their high-volume and autonomous production, the COTS 18650 cells from reputed manufacturers have impressive cell-to-cell consistency and uniformity, which eliminate the need for cell balancing and simplify battery charging. Cells are arranged in standard series-parallel or parallel-series configuration to design a battery of desired capacity and voltage with adequate redundancy. Custom Li-ion cells, on the other hand, have the advantages of tailoring the size and chemistry of the cell for the intended application, as was successfully done in the Mars surface

missions with low temperature electrolytes. Table-2 shows the performance characteristics of current Li-ion technologies. Current battery designs are prone to (thermal) propagation of the failure of a single cell to the entire module. Propagation-resistant designs are under development but will add to additional mass and volume of the battery. Even without the propagation-resistance feature, the battery-level specific energy is only 60-70% of the cell specific energy. With the high specific energy of ~250 Wh/kg from today's COTS 18650 cells, it is possible to achieve 200 Wh/kg at the battery level, with advanced packaging, e.g., with additively manufactured (3d printed) battery structures. Finally, only metal-encased cells are used thus far, and pouch cells, which are the preferred cell formats for the new technologies, are yet to be qualified for space use.

2.2 Advanced Rechargeable Battery Technologies

New battery chemistries have been evolving which can potentially improve both the specific energy and energy density beyond the current Li-ion technologies, as listed below:

- Si-C- Ni-rich nickel manganese cobalt (NMC) oxide 275 Wh/kg and 600 Wh/l
- Li -Ni-rich NMC cathode with liquid electrolyte 300 Wh/kg and 600 Wh/l
- Li-Ni-rich NMC cathode with solid electrolyte 300 Wh/kg and 650 Wh/l
- Lithium-Sulfur cells in liquid/solid electrolyte 350 Wh/kg and 650 Wh/l

Table-3 illustrates the projected performance of these technologies, as well as their technology readiness levels. Among these high energy technologies, solid electrolyte based batteries with Li anode offer the highest specific energies. Overall, despite the enhanced performance possible with these technologies relative

to Li-ion batteries, their availability at a TRL 5 by 2025 for the decadal missions is uncertain. Among the various systems, all solid state batteries with Li anode and solid electrolytes are the most promising to meet the energy, cycle life and safety targets of future NASA missions and likely to achieve technical maturity by 2025. *Li-ion batteries may benefit from further incremental growth at the cell level combined with efficient cell packaging designs and may provide 'safe' batteries with 200Wh/kg and good life characteristics. These batteries may lack adequate low temperature performance, and need to be modified with appropriate low-temperature electrolytes.* Additionally, there are a few high temperature (250-350°C) systems relevant to Venus missions: i) Sodium-Sulfur (Na-S) and ii) Sodium-Metal Chloride (Na-MCl₂), both fully developed for commercial applications with 100 Wh/kg and 1000 cycles, but not used yet in space. Li(Al)-FeS₂ molten salt batteries (465°C) are being developed at JPL for Venus and Mercury surface missions.

2.3 Li Primary Batteries:

Primary batteries are typically used for providing power in missions that require a single use of electrical power for a period of minutes to several hours, or even a few days. Primary batteries used in space missions are: silver-zinc (Ag-Zn), lithium-sulfur dioxide (Li-SO₂), and lithium-thionyl chloride (Li-SOCl₂). They have been used in planetary probes (Galileo, and

Huygens), sample return capsules (Stardust and Genesis) and landers (Mars Exploration Rover) and Deep Impact. Both Li-SO₂ and Li-SOCl₂ batteries have moderate specific energy (150–250 Wh/kg), excellent shelf life of ~10y and operate over a temperature range of –40°C to 60°C.

Advanced Li-primary systems under development include Li-CF_x, and Li-O₂, which offer higher specific energy: 500 Wh/kg (battery) for Li-CF_x and >600 Wh/kg for Li-O₂. While Li-O₂ is still at a low TRL, the Li-CF_x technology is now being developed for the Europa Lander mission concept. Table 4 lists the performance characteristics of the SOA and advanced primary batteries.

2.4 Fuel Cells

Viable fuel cell technologies under development for space applications include: polymer electrolyte membrane (PEM) fuel cells, solid oxide fuel cells (SOFC), and regenerative fuel cells (RFC) ES systems. Among these systems, H₂-O₂ PEM primary FC and RFC ES systems are more widely applicable, because of their performance and advanced stage of development, while SOFCs have unique role for Venus aerial and select surface missions due to high temperature operation and fuel flexibility. H₂-O₂ PEM primary FC are attractive for applications with dynamic power profiles and system sizes ranging from 100's Watts to kW-MW sizes (e.g., Ocean World landers) with potentially higher specific energy than primary batteries. RFCs present an enabling mass-efficient solution for high energy applications such as surface energy storage for future long-duration human lunar (Lunar Surface Initiative) and Martian missions. and can offer >2X specific energy vs. rechargeable batteries at the system level. It should be noted that since the energy storage and energy conversion portions of an RFC are separate and can be individually optimized for the application, the specific energy of similar systems can vary significantly depending on the anticipated power profiles and energy storage quantity. These values do not scale linearly based on solely energy storage quantities and can range from below 250 Wh/kg to over 550 Wh/kg.

2.5 Capacitors

Capacitors are typically used in most spacecraft to meet peak power demands. Tantalum capacitors (solid and electrolytic designs) were used in the Galileo and Cassini missions. The advantage of capacitors is their ability to supply high pulses over short durations repeatedly for hundreds of thousands of cycles. Supercapacitors, especially the most recent versions, have improved specific energy at the sacrifice of some power density. This is achieved through the substitution of one of the high surface area electrodes, with a lithium intercalating electrode. These capacitors, termed asymmetric or Li-ion capacitors, can achieve 15 Wh/kg and power density of 5-10kW/kg. The cycle life is many orders of magnitude greater than a Li-ion battery. A hybrid system of suitable capacitor and high-energy battery will have both high energy and power.

3.0 Energy Storage Requirements of NASA's Next Decadal Missions

The next decadal mission concepts to Outer planets, Inner planets missions, Mars, Moon and to Small Bodies are discussed below in terms of their environments and energy targets.

3.1 Energy Storage Needs for Inner Planet Missions

Venus orbital missions and high-altitude aerial missions are relatively benign, but the lower atmosphere and surface missions are the most challenging, contending with highly corrosive gases, high pressure (90 bars at the surface), high temperatures (465°C at the surface). However, at an altitude of ~55 km, where the winds are strong enough to enable aerial missions, the conditions are benign and earth-like with 0°C and 1 bar. If aerial missions are contemplated in lower atmosphere, then the batteries need to operate at higher temperatures (350°C) at an altitude of 15 km. Table-5 lists the desired ES technologies and their advancements for inner planet aerial and surface missions.

Table 5: Energy storage technology targets for future Inner Planet missions

Continued development of high temperature primary batteries, moderately high temperature rechargeable batteries will considerably enhance or even enable future Venus missions, and also support goals of the Venus Flagship Mission Study.

3.2 Energy Storage Needs for Outer Planetary Mission Concepts

There are two categories of outer planetary missions being considered for the next decade: a) Missions to Ocean Worlds and b) missions to the Ice Giants. Potential Ocean World mission destinations include: Enceladus, Europa, Titan, Ganymede, Callisto, and Ceres, while the Ice Giant destinations are Neptune and Uranus. Outer planet missions pose several technical challenges for energy storage systems, which include: a) long calendar life and cycle life capability, b) radiation tolerance (Jupiter system missions) and c) heat/radiation sterilization endurance. Table-6 lists the desired energy storage technologies and their advancements for outer planet missions.

Table 6: Performance targets of Energy Storage Technologies for future Outer Planet missions

Continued development of long-life Li-ion batteries and high energy primary batteries will enable future missions to Neptune, Saturn and its moons, Uranus, Jupiter and its moons. In particular, it will support “Flagship Concepts for Astrobiology at Enceladus”.

3.3 Energy Storage Needs and Technologies for Mars Missions

Possible Mars robotic missions the next decade include: a) Mars orbiters, b) potential Mars sample return missions (includes Mars ascent vehicles, landers, and sample-fetching rovers), c) Mars helicopters and other forms of proposed aerial vehicles, and d) human Mars precursor missions (large landers, rovers, In-Situ Resource Utilization [ISRU] demonstration missions, etc.). Mars surface missions pose different challenges for energy storage systems: low-temperature operational capability ($<-40^{\circ}\text{C}$), long-life, high specific energy and high energy density. In addition, Mars aerial missions require *very high* power capability ($>3000\text{ W/kg}$). Table-7 lists the requirements of energy storage technologies and their desired advances for Mars missions.

Table 7: Performance targets of Energy Storage Technologies for future Mars missions

Development of batteries with high specific energy combined with long cycle life, good low temperature performance, and high power are crucial for future Mars missions.

3.4 Energy Storage Needs for Small Bodies

Small bodies in our solar system include asteroids, comets, and dwarf planets. Possible missions include: a) Near-Earth Objects: Mega-multi-flyby, Multi-rendezvous, and Sample return, b) Main belt asteroids and Jupiter Trojans: Sample return, Multi-asteroid rendezvous, and Jupiter Trojan rendezvous, c) Comets: Comet Surface Sample Return and Nucleus Sample Return, d) Phobos and Deimos Sample Return, e) Dwarf Planets: Haumea flyby, and f) Centaurs and Trans-Neptunian Objects: Flyby. The ES system needs are:

- Rechargeable batteries with $\geq 250\text{ Wh/kg}$, cycle life of $>50,000$ cycles at partial DOD, and calendar life of >15 years for orbital/fly-by missions.
- Rechargeable batteries with $>250\text{ Wh/kg}$, >1000 cycles, calendar life of >5 years, wide operating temperature range (-40°C to 40°C) for landers and rovers.
- Primary batteries with $\geq 500\text{ Wh/kg}$, calendar life of >5 years, high specific power ($1,000\text{ W/kg}$) and wide operating temperatures (-40°C to 40°C).

Further development and demonstration of this capability would enable a new type of mission for landers on small bodies.

3.5 Energy Storage Needs for Lunar Surface Missions

Advanced ES systems will be needed for both rovers and central power stations. Power levels for stations can be expected to be >100 kW, which favor RFCs over batteries. Lunar surface missions present two challenges:

- Recoverable batteries with 300 Wh/kg and wide operating temperature (-100 to +160 C) with advanced thermal technologies, e.g., heat-pipe embedded additive manufacturing.
- RFCs with >300 Wh/kg at the system level, long life of >5 years, minimal or no required maintenance and the capability to operate over a wide temperatures (-173 C to +125 C).

These capabilities will enable long-term operations of central power stations. Additionally, the two concept studies, “Intrepid Planetary Mission (Lunar Rover)” and “Lunar Geophysical Network” will be powered by high specific energy batteries with COTS 18650 cells.

4.0 Summary and Recommendations

Further advances in ES technologies are required to fulfil the needs of future NASA planetary science and astrobiology missions in the next decade. Though some of these requirements are synergistic with the industry, many mission architectures and designs are unique, and warrant further improvements in lifetime, thermal capability, environmental compatibility, mass and volume of the ES devices. NASA PSD will need to undertake its own technology programs to alleviate these constraints, while leveraging the DoE / DoD efforts. Below are the recommended ES technologies, which will need to be developed to enable new mission concepts or enhance the current missions.

- Advanced high temperature primary and rechargeable batteries with a specific energy of 150 Wh/kg, energy density of 150 Wh/l, calendar life of 5 years and operating temperature of 400-465°C *to enable future Venus landers and probes.*
- Advanced primary batteries with a specific energy of 500 Wh/kg, calendar life of 10 years and operating temperature of -40 to 70°C *to enable future Ocean World lander missions, outer planetary probes and Sample Return missions (SRM).*
- Advanced regenerative PEM fuel cells with >300 Wh/kg and calendar life of 5 years *to enable future Lunar habitats.*
- Advanced rechargeable batteries with a specific energy of 250 Wh/kg, cycle life of 1000 cycles, calendar life of 10 years and operational over -10 to +100°C *to enable new Venus aerial (aerobot) missions and Lunar surface missions (where the batteries may be warmed at night, but are resilient to high temperatures during the day).*
- Advanced rechargeable batteries with a specific energy of 250 Wh/kg, cycle life of 50,000 cycles at ~40% depth of discharge, calendar life of 15 years to *significantly enhance* orbiter missions to Mars, Venus and various outer planets.
- Advanced rechargeable batteries with a specific energy of 200 Wh/kg, cycle life of 500 cycles, calendar life of 10 years and power densities of 3 kW/kg to *significantly enhance future Mars helicopters and outer planets aerial missions.*
- Advanced rechargeable batteries with a specific energy of 250 Wh/kg at 25°C and 150 Wh/kg at -40°C, cycle life of 1000 cycles and calendar life of 15 years to *significantly enhance future planetary (Mars) landers and rovers.*

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6.0 References

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