A Comparison of Radioisotope and Solar Array/Battery Power Systems in the Solar System

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Radioisotope Power Systems (RPS) are an invaluable resource for the exploration of our solar system. Providing both heat and electricity, spacecraft using RPS can operate where its impractical to use solar array and/or battery systems because of either limited solar illumination or mission durations which make a standalone battery impractical. This paper highlights the performance advantages which may come from using a RPS compared with a solar array/battery system. Included in this paper is an overview of the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), the Next-Generation RTG (NGRTG) and Dynamic Radioisotope System (DRPS). State-of-the-art (SOA) performance of solar arrays and batteries is discussed. Finally, a comparison of both solar cell/battery and RPS systems are made at a variety of locations, both orbital and on the surface of some planets and their moons within our solar system.

I. INTRODUCTION

Thermoelectric generators have an impressive history of providing power including the Voyager spacecraft Radioisotope Thermoelectric Generators (RTGs) which have operated for over 45 years. The only currently available RTG is the MMRTG and is powering both the Curiosity and Perseverance rovers on the Martian surface. Because of the cost and scarcity of plutonium higher conversion RPS are being studied. Two additional RPS development programs are under way at NASA called the NextGen RTG and the Dynamic RPS (DRPS). Primary differentiators between these generators and the MMRTG are total power produced, reduced degradation rate and increased specific power. Each system will be discussed and performance estimates made for these new generators.

Solar arrays are the standard power systems for use in the inner solar system. Solar arrays coupled with batteries for either shaded periods or peaking have traditionally been used from Mars inward in the solar system. Advances in both solar array technologies and energy storage have extended their use past Mars and recently missions have used solar arrays out to Jupiter with the Lucy and Juno missions as well as the upcoming Europa Clipper. A summary of the SOA in solar array and battery performance will be given along with some ancillary power system components.

II. RADIOISOTPE POWER SYSTEMS

In the United States, RPS uses Pu-238 fuel coupled to thermoelectric power convertors (called RTGs) to convert decay heat into electricity. The Pu fuel is placed within a General-Purpose Heat Source (GPHS) module to ensure that the Pu fuel remains intact in the case of an accident. Each GPHS produces 250 W of heat at beginning-of-life (BOL) and has a mass of 1.6 kg. The GPHS modules are stacked with different number of modules for each of three concepts discussed

II.A. Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)

The MMRTG shown in Figure 1 is a RTG capable of operating in both deep space and on bodies with an atmosphere (Ref. 1). MMRTG uses 8 GPHS centrally stacked and surrounded by thermoelectric modules. It nominally produces 124 W of power at BOL and has a mass of 45 kg. NASA's Curiosity and Perseverance Mars rover both use a single MMRTG and utilize both its electrical power output and waste heat to enable long duration operation on Mars. The MMRTG seals the Pb-Te thermoelectric modules with an inert cover gas to prevent the external environment from damaging the thermoelectrics. Sealing the thermoelectrics to allow their use in a wide variety of environments adds an important feature to the MMRTG although it also adds a single point failure mechanism that would quickly destroy the

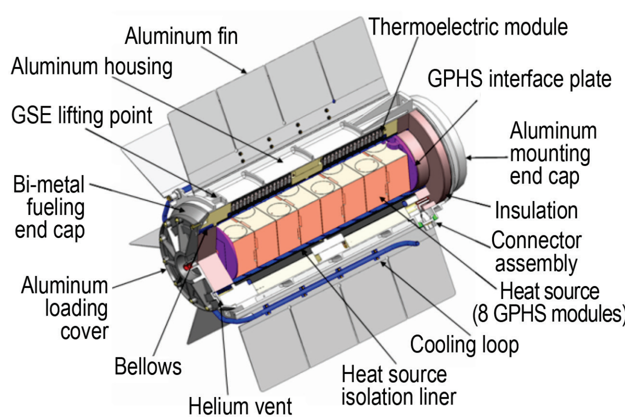

Fig. 1. MMRTG

thermoelectric materials if penetrated. For any mission, particularly long endurance missions or missions where the MMRTG isn't embedded within a spacecraft must be aware of the micrometeoroid environment and ensure penetration of the thermoelectric modules does not occur. While the MMRTG has the lowest specific power (W/kg) of any of the other two generators discussed its flight proven technology is an important resource for NASA missions. MMRTG will be the electrical power and heat source for NASA's upcoming Dragonfly mission to Saturn's moon Titan (Ref. 2).

II.B. NextGen RTG

The GPHS-RTG was a previously developed DOE RTG which used 18 GPHS modules radiatively coupled to Silicon Germanium thermoelectrics. The GPHS-RTG was designed for vacuum only operation and can therefore use multi-layer insulation to improve performance by allowing much higher thermoelectric temperatures when operating in a vacuum environment. GPHS-RTG has an impressive history of operational reliability from the Ulysses, Galileo and Cassini spacecraft to the more recent Pluto New Horizons. GPHS-RTG had the best specific power of any RTG developed to date with a BOL specific power of 5.3 W/kg. The Pluto-New Horizons mission was the last NASA mission to use GPHS_RTG and development was halted after the mission. Because of changes in the size of the GPHS module and the loss of the exact process to make the SiGe Unicouples, GPHS-RTG can no longer be produced. In 2016 and 2017 a study was performed to look at how an updated RTG would perform using these new larger GPHS modules (Ref. 3). This study resulted in NASA contracting both Lockheed Martin and Aerojet Rocketdyne to analyze in detail a design for a follow-on to the GPHS-RTG. At the end of the design phase, it was decided that rather than develop a completely new RTG design a new contract would be solicited to develop a similar design to the GPHS-RTG to reduce cost and risks with accommodation for the larger GPHS modules size and additionally to try and recreate the Si-Ge Unicouples used in the original GPHS-RTG design. In 2021 Aerojet Rocketdyne was awarded a DOE contract to develop this follow-on generator with the desire to have a first iteration available for a late 2020s mission (Ref. 4). The first generation of NextGen RTG's called Mod-1 will have performance like but slightly worse than GPHS RTG because of the increase in size of the GPHS. This allows high confidence that a generator can be available for the late 2020s.

The NextGen RTG will not have any of the single point failures associated with MMRTG and therefore very tolerant to micro-meteoroid and orbital debris however it is very sensitive to external atmospheric environments other than vacuum. The generator is filled with an inert gas during all ground operations on Earth and is vented after launch. This prevents gasses from infiltrating sensitive components within the generator. Just after launch when the generator is in a vacuum the cover gas is vented, this allows for the insulation effectiveness to improve, increasing the thermoelectric hot side temperatures and allowing He generated from the decay of Pu-238 be released to the environment. Because this study will consider using NextGen RTG on Icy World surfaces consideration must be given to any atmospheres either naturally or generated by the heat of the RTG. Nominally most of these bodies have very little atmospheres but with the addition of the RTG to the environment it may cause sublimation significant to affect the performance of the generator. A recent conversation with a RTG expert said the following: "It would generally seem that the physical process of water sublimation and diffusion into an RTG would be unfavorable, but the potential consequence of water as a strong oxidizing agent getting into a vacuum rated RTG is significant enough that further studies would be required to understand and properly mitigate this risk" (Ref. 5). Figure 2 shows a rendering of a NextGen RTG Mod-1.

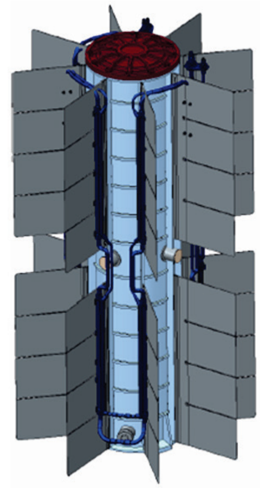

Fig. 2. NextGen RTG Mod-1

II.C. Dynamic Radioisotope Power System (DRPS)

NASA is currently considering using dynamic power conversion technologies coupled to GPHSs because of their potential to increase the heat to electric conversion efficiency (X4) extending the power output available from the current and future isotope production. Recent work at NASA GRC has focused on both Stirling and Brayton power conversion technologies (Ref. 6). Sunpower Inc, Athens, OH and American Superconductor (AMSC, Richland, WA) both have produced power convertors that may meet NASA's desire for a dynamic RPS. Sunpower contracted with Aerojet Rocketdyne to develop a generator concept while AMSC partnered with Teledyne Energy Systems Inc. The Brayton power conversion system was developed by Creare while the generator was developed by Aerojet Rocketdyne with support from West Coast Solutions for the controller. Of these power conversion technologies, the Stirling based systems appear to offer the most attractive combination of power conversion efficiency and specific power. The Brayton based power conversion RPS, while projected to meet the efficiency goals has a considerable projected mass disadvantage over the two Stirling convertors under development. The Department of Energy is responsible for all nuclear systems in the U.S. and DOE. Recently awarded Aerojet Rocketdyne a contract for a detailed study of promising dynamic power conversion convertors and then look at how these convertors would be assembled into a generator (Ref. 7). Once a down selection is made of the best available convertor a follow-on contract could lead to a hardware contract that would provide NASA with a new RPS generator. Requirements for the DRPS include the requirement for being multi-mission like the MMRTG with the addition of being capable of working at all locations on the lunar surface without modification. DRPS generators represent the biggest change from traditional RTG based RPS systems since their development. One of the features of RTG's is their individual TE elements are small and so a high degree of TE redundancy is possible within the generators. It is not possible to make dynamic power convertors on that scale and so the level of redundancy and therefore implied reliability is of concern. Unlike the previously developed Advanced Stirling Radioisotope Generator (ASRG) which had no redundancy, current efforts have focused on having generators with multiple convertors capable of sharing the heat source (Ref. 8). This allows for these generator concepts to have redundancy with the hopes of providing increased reliability and alleviate the need for spare generators. Each of the individual Stirling convertors has its internal He working gas sealed within the pressure vessel. Although MMOD are of concern for these generators the number of individual pressure vessels with the current concepts should greatly mitigates this risk. Thus, DRPS should fall between MMRTG and NextGen RTG with respect to MMOD risks. For this study we will focus on representing a DRPS by projecting performance from the contractors two Stirling based DRPS generator designs shown in Figure 3. Each design used superalloy Stirling convertors coupled to a stack of GPHS modules. These GPHS are radiatively coupled to the Stirling convertors which are attached to the housing of the generator. Shaking forces generated by the operation of the convertors are canceled by paring an opposing Stirling convertor operating out of phase with its counterpart. Unlike RTGs DRPS require an electronic controller to both modulate the Stirling convertors and convert the single-phase AC to 28 V DC for the spacecraft bus. These controllers are under development both at NASA GRC and the Applied Physics Laboratory (APL) (Ref. 8).

II.D. Generator Comparison

Each of the generators considered here have their own unique and compelling characteristics as discussed in their sections above. Table 1 shows a comparison of the three generators, their expected performance. Because both NextGen and DRPS are under development assumptions about both the number of GPHS and configuration were made. The performance parameters outlined in the Table is based upon the generators operating in a deep space environment. The reason for this is that the vast majority of RPS systems used have been sent to the outer planets with very little energy being imparted to the generator from the ambient environment. A notable exception being the Moon and Titan along with a brief discussion of Mars.

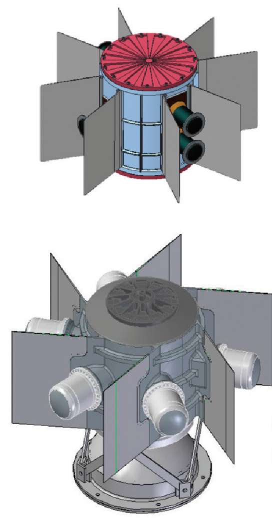

Fig. 3. DRPS concepts

TABLE I. COMPARISON OF RPS

	MMRTG	NextGen RTG Mod-1	DRPS
#GPHS	8	16	6
Convertor	Step 2 PbTe	Step 2 SiGe	Step 2 Stirling
BOL power output , watts	124	229	351
EODL power output, 17 yr	70	165	283
BOL efficiency	6.2%	5.7%	23.4%
BOL specific power, W/kg	2.7	4.1	3.7
Waste Heat, watts	1876	3772	1149

II.D.1. Moon

The lunar surface is a challenge for RPS because of the wide environmental temperature swings particularly at the equator. Notably the regolith covering the surface of the Moon is a good solar absorber and goes from a relatively benign 100 K during the long duration lunar night to over 380 K near the equator. Exacerbating this impact on a RPS is the high degree of adhesion of the soil to any external object where there is the possibility of soil transfer. For both the MMRTG and the DRPS special white paint coatings cover the external surfaces of the RPS to reduce the amount of solar energy imparted to the generator. These coatings typically reflect over 80% of the direct solar and albedo imparted to the generator. This is in sharp contrast to the lunar soil which absorbs about 90% of the solar energy. Any dust accumulation on the RPS heat rejection surfaces can drastically change the thermal environment each generator is subjected with the result of either reducing power or damaging the generator. Reference 10 discusses in detail how sink temperatures were estimated for the lunar surface (Ref. 10). Using the referenced values for both solar absorptivity and thermal emissivity sink temperature, power estimates were made during a single lunar day/night cycle located at the equator on the lunar surface. Figure 4 shows the power output drops from its 350 W at night to 320 W during the early morning and late afternoon at the equator during the 14 Earth-day daylight period.

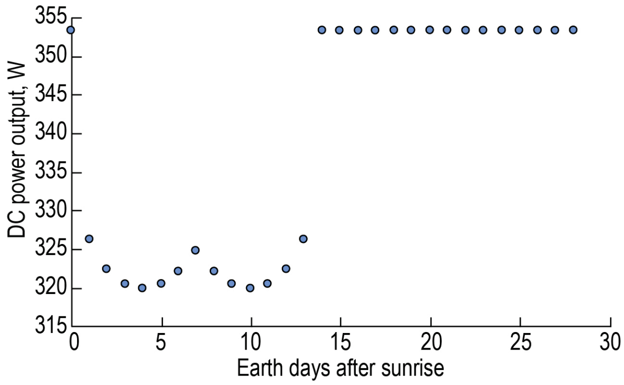

Fig. 4. Power output of a DRPS concept on the lunar surface at the equator

II.D.2. Titan

The moon of Saturn, Titan has a very thick atmosphere consisting mostly of nitrogen. Its atmosphere is 50% denser than Earths and around 100 K. Therefore, unlike the other bodies which have radiant heat transfer dominate, convection heat transfer is the primary means for removing heat from the RPS. Because these heat transfer coefficients are so much higher than radiant heat transfer the RPS placed upon the surface will have dramatically lower temperatures throughout their system and drive them below their qualified or desirable operating temperatures. The currently planned Dragonfly mission will use a MMRTG, but it will be surrounded by thermal insulation to prevent the very cold atmosphere from reducing the power output (because of changes in the thermoelectric properties) and reduce the effectiveness of the RTG waste heat recovery and keeping the components of the spacecraft warm.

At Titan, a DRPS with additional mission accommodation like the MMRTG on Dragonfly could be used on or near the surface. Unlike MMRTG, DRPS performance may be increased because of the lower temperature heat rejection which should both increase the efficiency and power output. Because of the unknows with respect to the final design of a DRPS for this study no increase in performance will be assumed.

II.D.3. Mars

Several RPS systems including the current MMRTG powered Curiosity and Perseverance have been used on Mars. Surface atmosphere temperatures vary from about –125 °C at the poles in winter to up to 20 °C near the equator. Although heat transfer on Mars is augmented by convection the very low-density atmosphere heat transfer is still dominated by radiation to the environment.

Mars has a thin surface atmosphere (0.6 kPa) relative to Earth , but the thermoelectric and the GPHS graphtic materials used in the GPHS RTG or NextGen RTG would interact with the environment and quickly destroy the generator. Because of this the MMRTG was developed to allow operation in the Martian surface environment. Its relatively lower performance is due to this accommodation. Mars however is the one planetary body which would slightly decrease performance of the MMRTG or DRPS when compared with deep space operation. For the Curiosity rover the power output from MMRTG varied from about 109-119 W or about an 8% variation during a Martian sol (Ref. 11). Most of the other planetary bodies which can be landed upon, except those noted have very little thermal input from either the ground or solar illumination and the RPSs should behave nearly identically to operation in deep space.

III. Solar Array and Batteries

Solar array power output is primarily driven by the solar intensity received. Figure 5 shows solar intensity as a function of location in the solar system with the solar intensity values for each body orbiting at the same average distance of the annotated planets. Because of the dramatic fall off in solar intensity ($1/r^2$) RPS systems become more compelling when power system mass is important to the spacecraft. In this study solar array efficiency and solar array specific power are used to characterize these arrays. In 2017 JPL performed a study looking at solar power technologies for future exploration and projected the SOA performance of arrays (Ref. 12). Table 2 is an update from the 2017 study using increased efficiency for the solar arrays and tabulates the SOA solar array efficiencies, solar array areal density and solar array specific powers used in this study.

A significant driver of the mass of solar powered systems is the requirement for energy storage during the periods when sunlight is not available. For bodies with slow rotation, such as the moon, the storage requirements to operate over the night period can be the dominant mass of a solar/battery power system. The SOA for rechargeable space batteries is Li-ion technology, which has flown as the primary energy source on a significant number of satellites and on unmanned planetary exploration missions. Relative to other battery chemistries, Li-ion cells offer high specific energy long cycle and shelf life, and low self-discharge rates. Since they are sealed cells, they also require no activation or special maintenance. SOA battery performance is listed in Table 3. Using a battery based on a 18650, Li-ion cell volumetric energy density is about 194 W-h/liter while energy density is 175 W-h/kg respectively (Ref. 14). Each of these battery systems must have a thermal enclosure in order to operate at their optimal temperatures. In this study insulation is included in the mass of the battery but radioisotope heater units are used to ensure operation at the battery's optimal temperatures. If the batteries are required to provide heat to keep themselves warm it would result in mass increases. These numbers are consistent with SOA solar array performance on NASA's Lucy Mission and use Northrop Grumman Space Systems UltraFlex solar arrays with its SolAero's high efficiency-triple junction ZTJ solar cells (Ref. 13).

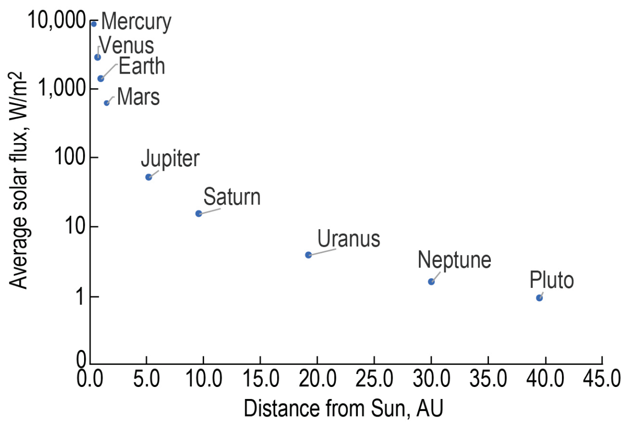

Fig. 5. Solar intensity as a function of location in the solar system

TABLE 2. Solar Array Performance

Fold Out Flexible Array	
Conversion efficiency, %	32
Areal power density at 1 AU, W/m^2	415
Specific power at 1 AU, W/kg	184

TABLE 3. Battery Performance

Lithium-Ion Battery SOA	
Specific energy, W-h/kg	175
Gravimetric energy density, W-h/liter	194
Depth-of-discharge, %	80
Charge/discharge efficiency, %	90

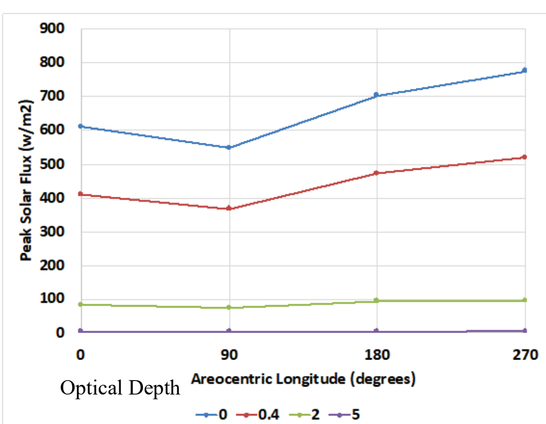

Fig. 6. Peak solar flux as a function of time of year

III.A. Solar Array Environmental Interactions

Generally, the duration of day/night cycle and the distance from the Sun drives solar array/battery sizing. Only a few surface locations in the study have atmospheres enough to attenuate the solar flux reaching the planets/moon's surface. The few special cases noted here are Mars and Titan.

III.A.1. Mars

Mars has a similar day/night cycle to Earth , but the solar flux is about 1/3 that at Earth above the atmosphere. Solar powered rovers and landers have demonstrated their utility using only battery power during the night. However, due to the low nighttime temperatures on Mars, particularly during winter, solar-powered rover missions (although not lander missions) to date have incorporated Radioisotope Heater Units (RHUs) to supply additional heat to keep the batteries at operational temperature(Ref. 15). For long duration operation these vehicles will need to plan on operating through Martian dust storms which can greatly reduce the solar flux on vehicle. Dust storms on Mars include local storms, which are of short duration and cover only small areas; regional storms, which cover larger areas and have a longer duration; and global storms, which cover all, or nearly all, of the planet, and can last for a month or more. These planet-encircling global storms occur on the average about once every three Martian years (5.6 Earth years). Previous solar-powered rover missions to Mars (e.g., the Mars Exploration Rovers) have survived these storms by the strategy of going into low-power "hibernation" mode during the periods of high dust opacity, and only returning to operation after the storm has ended. One method for estimating the solar flux on a body on the surface of Mars is to represent the attenuation of solar flux by optical depth. Optical Depth is an exponential multiplier to the direct beam irradiance outside the atmosphere (Ref. 16). Optical depth values vary from about 0.4 for a clear day on Mars to 5.0 for a global dust storm. An optical depth of 5 is used to estimate an intense dust storm although the largest recorded dust storm which occurred in 2018 which caused the Opportunity rover to stop working had an estimated optical depth of >9 (Ref. 17). Figure 6 shows the solar flux on the surface of Mars at various seasons during the Martian year as a function of areocentric longitude (Ls) at the equator. Where 'areocentric longitude' refers to the time of year, where Ls = 0° indicates the beginning of northern hemisphere spring on Mars and Ls = 180° indicates the beginning of northern hemisphere autumn on Mars.

III.A.2. Titan

Because of Titan's thick atmosphere much of the solar energy arriving from the Sun is attenuated at the surface. Solar energy arriving at the radius of Titan but outside its atmosphere is on average about 15 w/m^2. This energy is attenuated about 10-fold at the surface to about 1.5 w/m^2 due to its very thick atmosphere (Ref. 18). This in practice makes solar arrays for any significant power generation extremely prohibitive.

IV. SOLAR SYSTEM

Our solar system contains 8 planets. Of these only Mars, the Earth and Venus have solid surfaces and have a significant atmosphere. The remaining either have very little atmosphere or are gas giants with no solid surface. Mercury has very little atmosphere with a surface pressure of 0.5 nPa and surface temperatures vary from about –100 to 427 °C at the equator. ecause of the proximity to the Sun, operation for any of the RPS power systems discussed during daylight on Mercury would be a significant challenge requiring a redesigned system, which will not be considered here. Mercury does have permanently-shadowed polar craters, and a RPS system could reasonably be operated on a landed mission in these locations. During darkness on Mercury which lasts 1408 h the operation of any of the candidate RPS is possible and the performance should be near that of deep space operation (Ref. 19).

Venus has a very thick atmosphere consisting mostly of carbon dioxide and has a surface temperature of 500 °C and surface pressure of 95 bars. Because of this none of the RPS considered here can work upon the surface of Venus and its surface operation is excluded from this study although the possibility fo redesign of such systems for Venus surface operations has been proposed (Ref 19). It may be possible to operate a Multi-Mission RPS in the upper atmosphere but accommodations like those discussed earlier for lunar operation may be required as well as accommodations to interactions with the upper atmosphere composition on Venus.

In our solar system there are over 171 moons (Ref. 20). Of these many moons only 10 have atmospheres. The Moon, Ganymede, Europa, Callisto, Rhea, Dione, Enceladus, and Titania all have extremely thin atmospheres and these atmospheres should not interfere with operation of the RPS discussed with the exception being icy world water sublimation discussed earlier. Triton and Io have somewhat thicker atmospheres and would likely prevent a NextGen RTG from long duration operation. Most moons of the solar system are tidally locked, so the day equals the orbital sidereal period. Uranus is unusual in that its axial tilt is so high that on its satellites the sun will rise and set only once per Uranus yearunless the surface location is within about 8° of the equator. Pluto similarly has such a high axial tilt to the plane of its orbit that any surface object more than 33° is in the polar regions (Ref. 21).

For this study the distance from the Sun and day/night cycle of a body can be used to estimate both array and battery mass and area. Figures 7 shows the Siderial period of each of the locations considered. A comparison can be made between array mass and battery mass for each location. Figure 8 shows this comparison for an equatorial location with a 50%/50% day/night period. Finally, Figure 9 shows a mass comparison of many of the major bodies in the solar system using either RPS or solar Array/battery power systems.

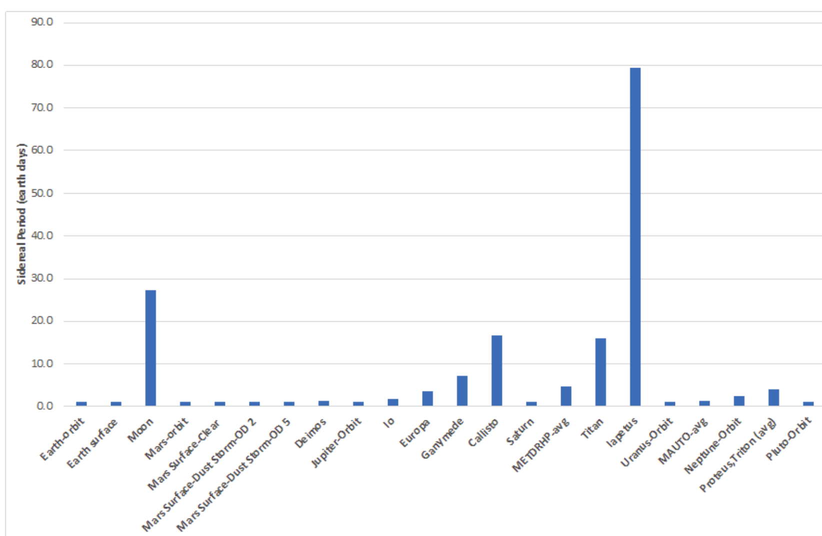

Fig. 7. Sidereal period of selected solar system bodies

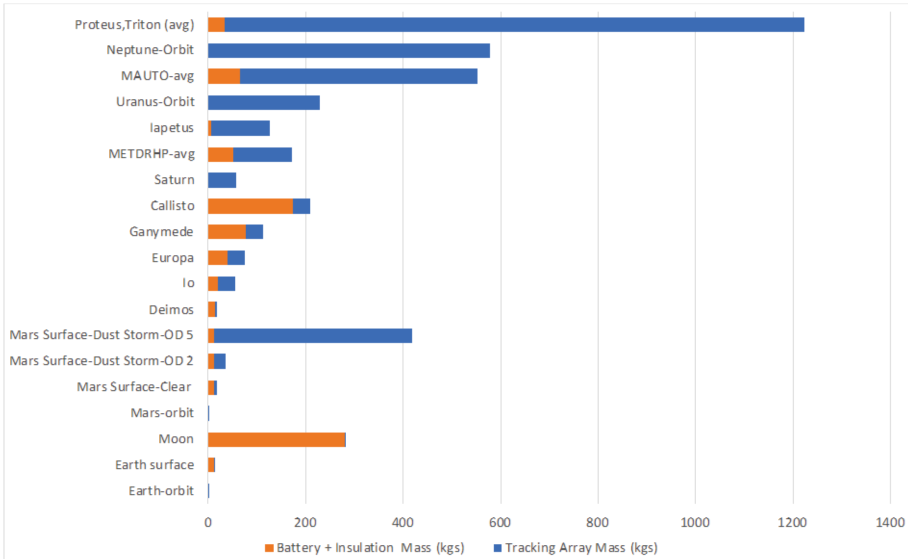

Fig. 8. Comparison of battery and solar array mass as a function of location

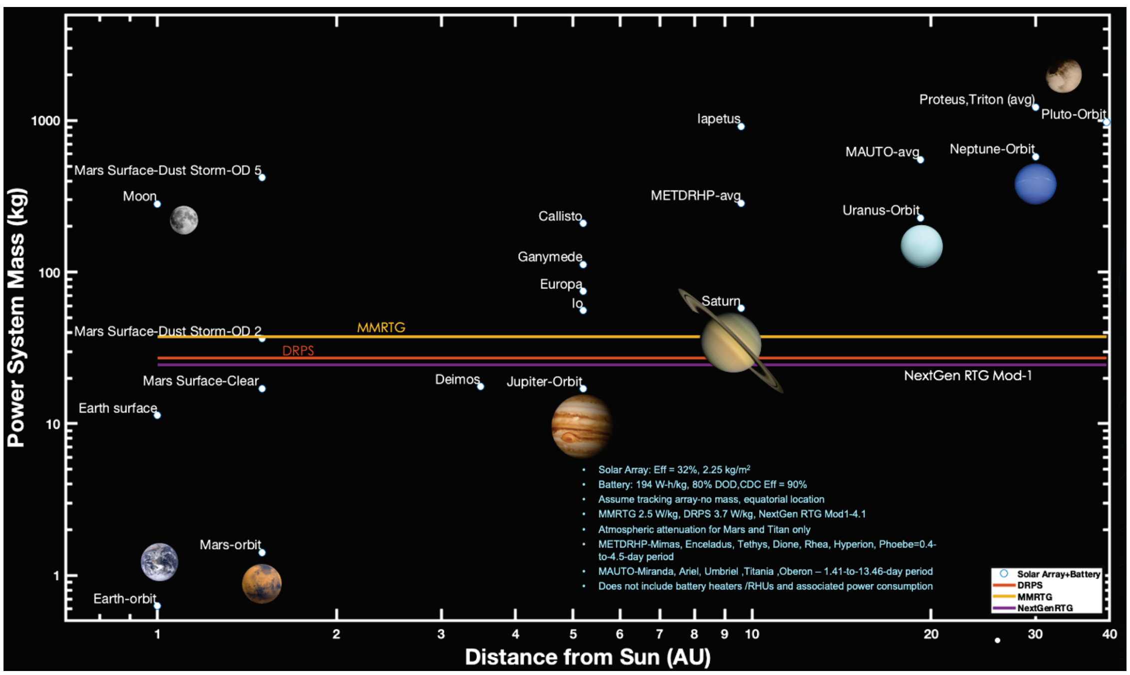

Fig. 9 Comparison of RPS and Solar Array Masses to Provide 100 W

Each is located at the equator and required to produce 100 W of power continuously to the spacecraft. Note that even for the lunar surface and Mars during a global dust storm RPS has a compelling mass advantage over their solar array/battery counterparts. As the distances from the Sun grow large arrays accompanied by large battery systems result when the duration of the night is many Earth days long. Iapetus is a prime example with its 80-Earth day period requiring both a very large array and a large battery system with a mass of almost 1000 kg to supply 100 W of power. A huge variety of trades are possible by varying the power required during day/night periods and operation away from the equator. Future work will include projecting solar array/battery and RPS into the future along with moving away from the equators of these bodies.

The discussion here has focused on electrical power requirements, but the heat energy directly generated by radioisotope systems can also be of significant benefit to outer solar system missions, which require heat to survive if night-time operation is required (Table 1.). This is also an enabling technology for survival and operation during the lunar night, wehre existing battery technologies would be subject to freezing at the ~100 K night-time temperature (Ref 23.)

V. Conclusions

Recent work discussing the utility of RPS has focused upon their utility where solar intensity is low. For RPS systems this is only part of the study as the day/night cycle can have a dramatic impact on the power conversion subsystem mass as close as the lunar surface or where solar attenuation is dramatic due to the local environment. This analysis shows that many locations throughout the solar system can benefit for RPS and they will continue to play a role in the exploration of our solar system.

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