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Space Power Heritage Study Final Results

Marc R. Hayhurst, Robert E. Bitten, and Eric M. Mahr
Aerospace Corporation, El Segundo, California

Vincent J. Bilardo, Jr.
Aerospace Corporation, Cleveland, Ohio

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Executive Summary

Selection of RPS for a given mission depends on many factors, including the ability to meet science requirements and ease of design integration, policy, schedule, cost, and risk. The goal of this study was to determine how much each of those factors influence the decisionmaking process and if any stand out more than others. Based on the analysis of the data collected, in general, electrical power subsystem (EPS) cost appears higher for RPS systems than it does for solar systems. Through conducting case studies, it seems that unique mission design and planned science have the greatest impact on the selection of RPS. Among five separate cases, there was no common reason for the choice of power source; however, primary decision factors included: cost, availability of RPS, and planetary protection. One prominent example is the Mars Science Laboratory (MSL) mission, which has been enabled by RPS, as solar-powered systems did not meet mission requirements due to sunlight and thermal constraints. In addition to the data analysis and case studies, development of MOEs was also undertaken. This resulted in two MOEs: one based on cost of RPS versus solar, and one based on science mission cost-effectiveness (SMCE). Using the first MOE, analysis shows that RPS is most cost-effective for outer-planet orbiter missions (to Saturn and beyond). Utilizing the second MOE shows that, even at a higher cost, RPS enables large missions with multiple instruments operating over a long operating life, and therefore provides substantial science value. This MOE assessment also shows that science value for RPS is higher per mission. However, SMCE of RPS versus solar is similar when looking at a large set of missions. Given the overall results of this study, it can be concluded that, if the cost of RPS were reduced and performance enhanced, RPS systems could be more readily adoptable for a broader range of missions.

Contents

Figures

Tables

1. Introduction

At the request of the Radioisotope Power Systems (RPS) Program Office at the NASA Glenn Research Center (GRC), The Aerospace Corporation (Aerospace) performed a study of spacecraft power system heritage. The primary goal of the study was to investigate the historical decisionmaking process behind choosing either a solar-based or RPS-based power system for planetary missions. The study was conducted as a multiphase effort. Phase I focused on feasibility, where cursory data exploration was conducted and it was determined whether there was sufficient data to support further work. Phase I concluded with a workshop at NASA GRC, where continuation to Phase II was approved. Phase II consisted of detailed data collection, case studies, and measure of effectiveness (MOE) development. The final results of Phase II were presented at the Johns Hopkins University Applied Physics Laboratory (JHU/APL) to members of the NASA RPS Program Office and the RPS Surrogate Mission Team (SMT). The final results of this study have been captured in this report, which is available for full and open release. Additionally, a full briefing package provides the same details of this document. This briefing package includes an appendix that includes data not for public release, which was used to provide detailed answers to questions raised during this study. The results of these inquiries are discussed in this document, but the proprietary data is not included. Finally, an executive summary package is also publicly available, which was used to present the results of the study at the 2018 Aerospace Space Power Workshop.

2. Data Collection Overview/Trends

2.1 Data Collection Overview

Initial data collection targeted 16 RPS missions (Table 1) and 18 solar missions (Table 2). To make the data collection task manageable and most relevant to the current time frame, collection for solar missions was limited primarily to those launched since 2000, with a few exceptions. Data collection for RPS missions however, was expanded to all years, as there are many fewer RPS missions than solar. Table 3 shows the data parameters the study sought to collect. These parameters included a mix of cost, technical, and other qualitative parameters, which were meant to provide context about each mission and be used in data analysis and MOE development.

The primary sources for the data include the NASA Cost Analysis Data Requirements (CADRe) reports, original documents from the missions, the NASA Air Force Cost Model (NAFCOM), and other official open-source documentation such as project websites or published papers. Most qualitative data about the missions was easily obtained. For example, the science objectives and nominal mission duration parameters were 100% populated for all missions. Most technical data was also found in CADRe or other sources. For example, solar array area was available 89% of the time, power generation mass was available 91% of the time, spacecraft wet mass was available 94% of the time, and spacecraft dry mass was available 97% of the time. Cost data availability was the most challenging aspect for many missions. For example, spacecraft bus cost was available 83% of the time, power subsystem cost was available 77% of the time, and power generation cost was available 17% of the time.

Some individual missions had data availability and other unique aspects about them that led to them being dropped from the database. The Apollo missions had no reliable source of information available. Ulysses had many foreign contributions, and power subsystem data was not available. The Mars Exploration Rover (MER) missions were also excluded, since they are difficult to categorize as they used solar for power and radioisotope heater units (RHUs) for thermal management. Mars Odyssey EPS cost is also much lower than all others, but it is not understood why.

The remaining data set with power subsystem cost includes 7 RPS missions and 18 solar missions. For RPS, the missions include Cassini, Galileo, MSL, New Horizons, Voyager, Pioneer, and Viking. Note that Voyager 1/2, Pioneer 10/11, Viking 1/2 are counted as one spacecraft each; although they are separate missions, the designs are identical, and it did not make sense for the individual spacecraft to be counted separately for many of the metrics. The missions that these spacecraft flew, however, were unique, and the operational months of each are considered for the SMCE metric. For solar, the missions include CONTOUR, Dawn, Deep Impact, Genesis, GRAIL, Juno, Kepler, LADEE, LCROSS, LRO, Magellan, Mars Odyssey, MAVEN, MESSENGER, MGS, MRO, OSIRIS-Rex, and Phoenix.

Table 1. RPS Missions

RPS Missions				
Mission	Power System Type	Launch Year	Destination	Program
MSL	RPS	2011	Mars	Mars
New Horizons	RPS	2006	Pluto	New Frontiers
Cassini	RPS	1997	Saturn	
Ulysses	RPS	1990	Sun	
Galileo	RPS	1989	Jupiter	
Voyager 1	RPS	1977	Jupiter/Saturn	
Voyager 2	RPS	1977	Jupiter/Saturn/Uranus/Neptune	
Viking 1	RPS	1975	Mars	
Viking 2	RPS	1975	Mars	
Pioneer 11	RPS	1973	Jupiter/Saturn	
Pioneer 10	RPS	1972	Jupiter	
Apollo 16 LSEP	RPS	1972	Moon	Apollo
Apollo 17 LSEP	RPS	1972	Moon	Apollo
Apollo 14 LSEP	RPS	1971	Moon	Apollo
Apollo 15 LSEP	RPS	1971	Moon	Apollo
Apollo 12 LSEP	RPS	1969	Moon	Apollo

NASA RPS missions all years
16 Total

Table 2. Solar Missions

Solar Missions				
Mission	Power System Type	Launch Year	Destination	Program
OSIRIS-REx	Solar	2016	Asteroid	New Frontiers
MAVEN	Solar	2013	Mars	Mars Scout
LADEE	Solar	2013	Moon	Lunar Quest
GRAIL	Solar	2011	Moon	Discovery
Juno	Solar	2011	Jupiter	New Frontiers
LRO	Solar	2009	Moon	Lunar Quest
Kepler	Solar	2009	Earth-trailing	Discovery
LCROSS	Solar	2009	Moon	
Phoenix	Solar	2007	Mars	Mars Scout
Deep Impact	Solar	2005	Asteroid	Discovery
MRO	Solar	2005	Mars	Mars
MESSENGER	Solar	2004	Mercury	Discovery
MER	Solar	2003	Mars	Mars
CONTOUR	Solar	2002	Comet	Discovery
Genesis	Solar	2001	Sun-Earth L1	Discovery
Mars Odyssey	Solar	2001	Mars	Mars
MGS	Solar	1996	Mars	Mars
Magellan	Solar	1989	Venus	

NASA Solar missions since 2000*
18 Total

Table 3. Data Collection Parameters

Programmatic	Power System Type		
	Launch Year		
	Destination		
	Program		
	Science Objectives	Baseline	
		Threshold	
	Nominal Duration	(years)	
	Extended Duration	(years)	
	Design Choices for Emissions		
	Planetary Protection Impacts		
	Radiation Environment		
Cost	Mission	(FY17$M)	
	Spacecraft	(FY17$M)	
	Launch Costs	(FY17$M)	
	Operations	(FY17$M)	

System	Wet Mass		(kg)
	Dry Mass		(kg)
	Power Generated		(W)
	Thermal Rejection		(W)
	Stowed Dimentions		(m x m x m)
	Deployed Dimensions		(m x m x m)
Power	Generation Technology		
	Solar Array	Mounting Config	
		Area	(m^2)
	Cost	Total	(FY17$M)
			(%)
		Generation	(FY17$M)
			(%)
	Mass	Total	(kg)
		Generation	(kg)
	Planetary Protection Cleanliness		
	Failures / Degradation / Anomalies		

2.2 Data Collection Trends

This study attempted to slice the data in a variety of different ways. From the various analyses performed, the three most salient metrics are presented. These include: EPS mass as a percentage of spacecraft bus mass, EPS cost as a percentage of spacecraft bus cost, and EPS subsystem cost per EPS subsystem mass (FY17$M cost per kilogram). From comparing RPS versus solar with these metrics, the following trends have been observed:

- EPS mass as a percentage of spacecraft bus mass is comparable - RPS = 27%, Solar = 24%
- EPS cost as a percentage of spacecraft cost is higher for RPS - RPS = 26%, Solar = 11%
- EPS cost per EPS mass (FY17$M per kg) is higher for RPS - RPS = $0.91, Solar = $0.20

The three plots shown in Figure 1, Figure 2, and Figure 3 discuss these metrics in detail, with respect to the overall database. The spacecraft bus mass excludes the mass of any payload elements to draw a uniform comparison of each mission. The same is also true that the comparison of EPS cost and spacecraft bus cost also excludes any payload elements. On each of the three plots, the RPS mission names have been highlighted blue to distinguish them from solar missions. For the RPS missions, it is noteworthy that the mass includes all EPS subsystem elements as well as the RPS generation source, such as a radioisotope thermoelectric generator (RTG). The same is true of cost, as all costs including those of the Department of Energy (DoE) for RPS are included. This is important to understand, as individual NASA projects may consider the cost of an RPS system outside their own budget, as RPS is generally procured in a somewhat external fashion—much like NASA procures launch vehicles for individual science missions. However, the full costs of these elements have been included to draw a fair comparison of the full cost of solar versus RPS systems.

In each of these three plots, the metric is plotted on the X-axis, with each of the data points (missions) ordered from least to greatest. On the Y-axis, a percent rank has been computed. This is a simple calculation of individual data point order/rank divided by the total number of data points (e.g., with 10 data points, data point 1 = 1/10 = 10% rank, data point 2 = 2/10 = 20% rank…). Plotting the data in this manner provides a sense of how the calculated average compares to all the individual data points in the data set, and generally results in an S-shaped curve.

Figure 1 shows the plot of the EPS mass as a percentage of the overall spacecraft bus mass. As can be seen here, the blue RPS missions are generally scattered throughout the plot. The average of the overall data set (red triangle), solar mission average (yellow square), and RPS mission average (green square) are clustered about the middle of the data set. As the solar average is 24% and the RPS average is 27%, this led to the conclusion that RPS and solar are comparable in terms of EPS mass as a percentage of the overall spacecraft bus mass. Also noteworthy, Pioneer 10/11 appears at the top end of this curve. It was the earliest unmanned RPS mission to explore the outer solar system. The overall spacecraft mass indicates it was relatively small compared to modern spacecraft, as the overall space vehicle mass was approximately 260 kg including the payload with the bus itself weighing approximately 192 kg. The EPS carried 4 SNAP-19 RTGs weighing 54 kg and with additional EPS components, bringing the total EPS mass to 91 kg—which constitutes almost half the bus mass.

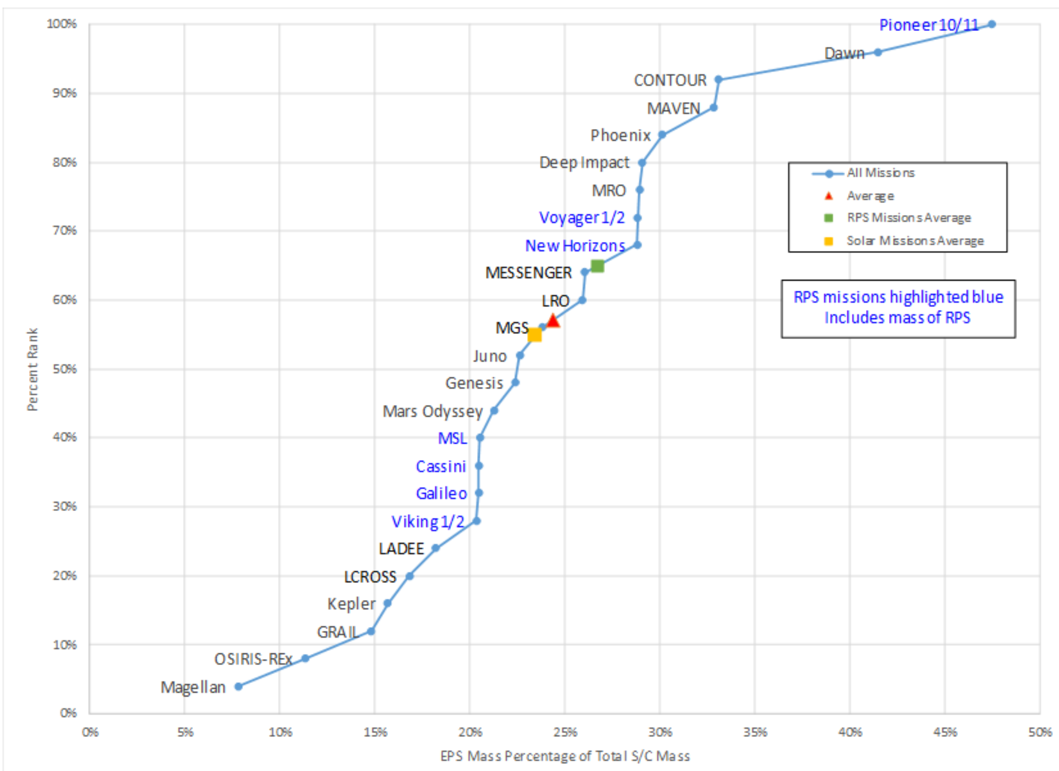


Figure 1. EPS mass percentage of total spacecraft bus mass.

Figure 2 shows a plot of the EPS cost as a percentage of the overall spacecraft bus cost. This plot reveals a different trend as compared to the mass in Figure 4, as the blue RPS missions are no longer scattered about the dataset—with most clustered at the top end. The RPS average is also at the top end of the curve, while the solar average is much farther down. This led to the conclusion that RPS cost as a percentage of spacecraft bus cost is much higher for RPS at 26%, versus solar at 11%. Notably, one data point that stands out at the top end of the curve is the New Horizons mission, for which the EPS cost constitutes almost 50% of the overall spacecraft bus cost. Investigation of this data point revealed that it is so much higher than others primarily because it is the only non-flagship mission to use an RPS system. Intended to control cost, New Horizons was procured as a cost-capped mission under the NASA New Frontiers program, while most of the other RPS missions were directed flagship-class missions, which tend to be costlier. When comparing the overall bus cost of New Horizons with the other missions in the dataset, it is in family with other cost-capped New Frontiers missions such as OSIRIS-Rex. Also, when comparing its EPS cost with other missions, it is also in family with the other flagship missions such as MSL. For these reasons, the percentage of EPS cost versus overall bus cost is much higher for New Horizons. The detailed data used in this investigation is also included in the non-public appendix to the chart package.

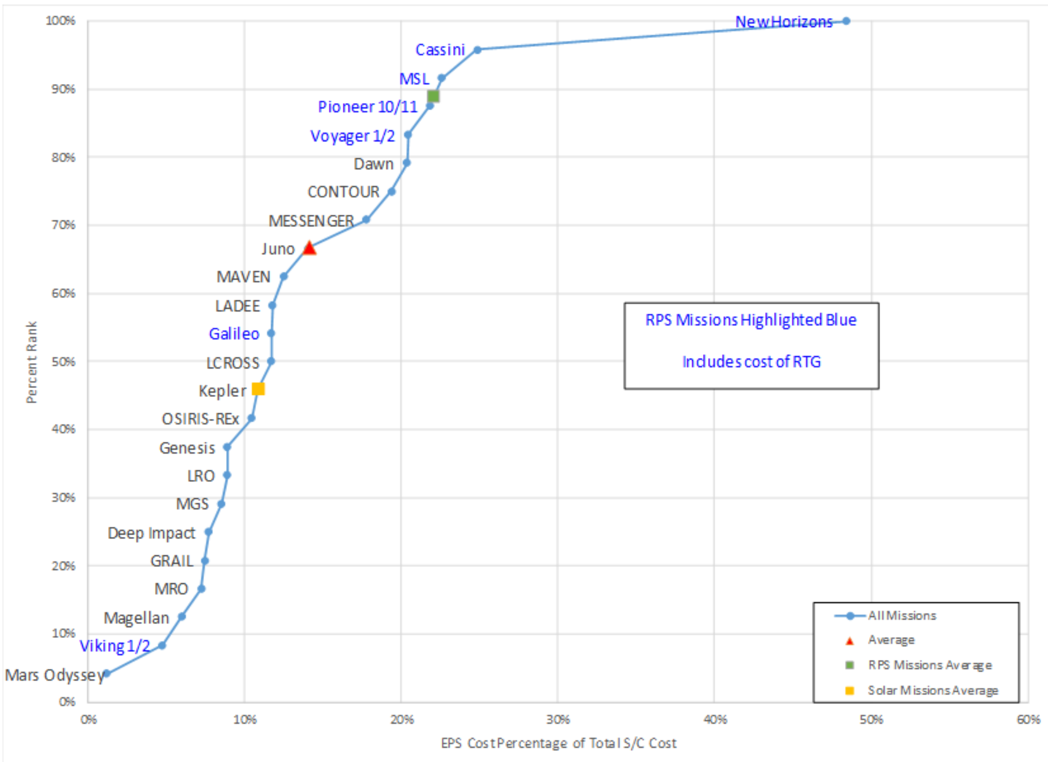


Figure 2. EPS cost percentage of total spacecraft cost.

Finally, Figure 3 shows a plot of the EPS cost per EPS mass (FY17$M cost per kilogram). In this plot, the clearest break between RPS and solar is observed, as the blue RPS missions are all clustered at the top end of the curve (except for one solar mission). The solar missions are all clustered in a fairly vertical fashion at the bottom end of the curve. In this dataset, the average cost per kilogram for solar EPS was found to be $0.20 FY17$M, and RPS was found to be much higher at $0.91 FY17$M.

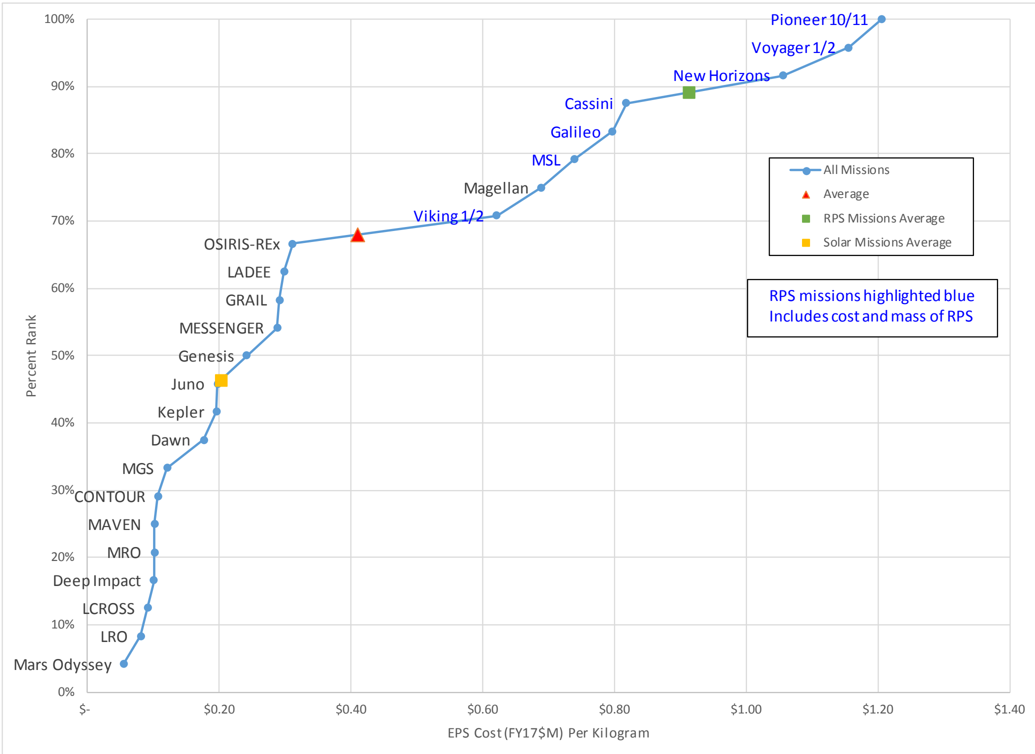


Figure 3. EPS cost per EPS subsystem mass.

This study also assessed trends by NASA center and mission class. The trends are similar to those for the overall dataset. However, most slices were too small to draw meaningful results. By Center, APL and Ames RPS had only one mission each (New Horizons and Pioneer 10/11, respectively). GSFC has flown no RPS missions to date. By mission class, all flagship-class missions are RPS, except for Magellan. Also, large-class RPS missions are only New Horizons and Pioneer 10/11. There are no medium-sized (Discovery) RPS missions. The details of these additional analyses are also contained in the non-public appendix.

3. Case Studies

3.1 Case Studies Overview

Case studies with actual personnel were performed to get an understanding of the decisionmaking process to choose RPS or solar for flown and planned missions that considered the two architectures. This was intended to understand the trades and differences in operational complexity between RPS and solar.

The missions identified RPS/solar decision:

- RPS to solar: PSP and Europa Clipper
- Solar to RPS: MSL
- Trade space exploration: Juno and Europa Lander
- RPS/solar operational complexity: MSL and MER

This study developed a list of questions to inform/guide the interviews. Interviews were performed either in person or via phone with the following individuals:

- MSL: Dave Woerner (JPL) and Loren Jones (JPL) - MMRTG Office Manager
- MER: Dave Woerner (JPL) and Loren Jones (JPL) - MMRTG Office Manager
- Europa Clipper: Greg Carr (JPL)
- PSP: Jim Kinnison (APL) – Mission Systems Engineer
- Europa Lander: Sam Thurman (JPL) – Project Manager
- Juno: Scott Bolton (SwRI) – Principal Investigator

Based on information gathered during the initial interviews, follow-up discussions on MSL and PSP on direction to use RPS were held with the following individuals:

- MSL: Len Dudzinski (NASA HQ) – Program Executive
- PSP: Ralph McNutt (APL) – Space Physicist

Table 4. Case Studies Overview

Mission	Background	Decision Criteria
Mars Science Laboratory (MSL) Launch: 2011 Target: Mars Power Source: RPS – MMRTG	• Studies started in 2000 for Mars Smart Lander • Wanted to consider a wide range of landing sites to look for water	• RPS chosen primarily due to desire not to limit the landing site • Best choices for looking for water reside in higher latitudes of northern hemisphere • Solar only feasible at lower at lower latitudes
Europa Clipper Launch: 2020's Target: Europa (Jupiter) Power Source: Solar	• Performed formal trade study evaluating 5 RPS, solar, and hybrid options	• Cost • Not significantly enabling to perform mission • If cost and schedule criteria were eliminated RPS would have ranked highest
Parker Solar Probe (PSP) Launch: 2018 Target: Sun Power Source: Solar	• Originally designed to swing by Jupiter and flyby the sun • At the time RPS was thought to be the only way	• Cost reduction direction from NASA HQ • Solar presumed to be the cheaper option • Able to develop trajectory that used Venus flybys • Also guided by availability of plutonium for RPS
Europa Lander Launch: 2020's Target: Europa (Jupiter) Power Source: Batteries (Lander) / Solar (Carrier)	• Performed a broad review of options for the both the carrier and the lander	• Planetary protection was a primary concern due to possible effect on potential indigenous life • Heat from RPS could have melted ice creating unstable footing • RPS would have enabled increased surface time to do long-term science (e.g., seismometry) • Carrier followed decision made for Europa Clipper

Mission	Background	Decision Criteria
Juno Launch: 2011 Target: Jupiter Power Source: Solar	• Baselined as an RPS mission given guidance of 2003 New Frontiers AO • Sought to demonstrate solar was a viable fallback given uncertainty of RPS development timeline	• Assumed proposing RPS would lead to the mission not being selected if RPS would not be available on time • Would have preferred RPS as using solar at Jupiter is more operationally complex

For the choice of power source, the discussion was focused on the decisionmaking process and not any difficulties encountered during development resulting from the decision. Table 4 provides a high-level summary of the individual case studies, and the details of each are included in the following sections.

3.2 Mars Science Laboratory (MSL)

Figure 4. Mars Science Laboratory[1].

<u>MSL Case Study Notes (Solar to RPS):</u>

- Studies started in 2000 for the Mars Smart Lander. In 2002, JPL was directed by NASA HQ to start looking at RTG, and a memorandum was signed with DOE.
- MMRTG allowed for a wider range of landing sites, thus providing an opportunity for more science. Initially, it was thought to be +/- 60 degrees, but turned out to be limited to +/- 30 degrees due to heating needs.
- The use of RTG is size-dependent, which made sense for MSL, but not for MER or Mars Pathfinder. MER first sized power system and found, based on how the solar panels could be arranged on the top deck, that RTG was not needed—RTG was not worth the mass.
- MSL started with 2 MMRTGs and solved the mass problem by descoping 1 unit. This was enabled by allowing greater battery depth of discharge (DOD).

[1] Image Credit: NASA/JPL-Caltech/MSSS, https://mars.nasa.gov/msl/multimedia/images/?ImageID=7658

- The impact to launch vehicle cost was thought to be $50M. However, this study could not find further breakdown of additional cost.

- The launch pad integration was a big consideration, as MMRTG was integrated 7 days before launch. Two doors were needed—1 for the launch vehicle and 1 for the aeroshell. There was a complete backup power generator to ensure power would be available for cooling. Mock-ups were built and practiced for a year in advance to check fit and work procedures.

- The MMRTG was cooled during the 2-year launch delay to minimize power loss: 124 W fueled, with 114 W available on the surface.

- The REMS instrument has an anemometer that can provide a false reading, since it sees the heat plume off the MMRTG.

- The MMRTG heat plume provides some protection from dust, since only the heaviest dust goes through the plume to land on the radiator.

- The choice of RPS for MSL was primarily driven by the desire not to limit the landing site potential. The goal was to look for water, and many of the best areas are in the northern hemisphere at the higher latitudes. RPS allows a much larger fraction of the surface to be considered. Solar power limits landing sites to lower latitudes. RPS enabled the increased potential for science discovery. NEPA authorities (JPL & NASA HQ) required solar to stay on the table in order to be formally traded against RPS for NEPA documentation purposes.

3.3 Mars Exploration Rover (MER)

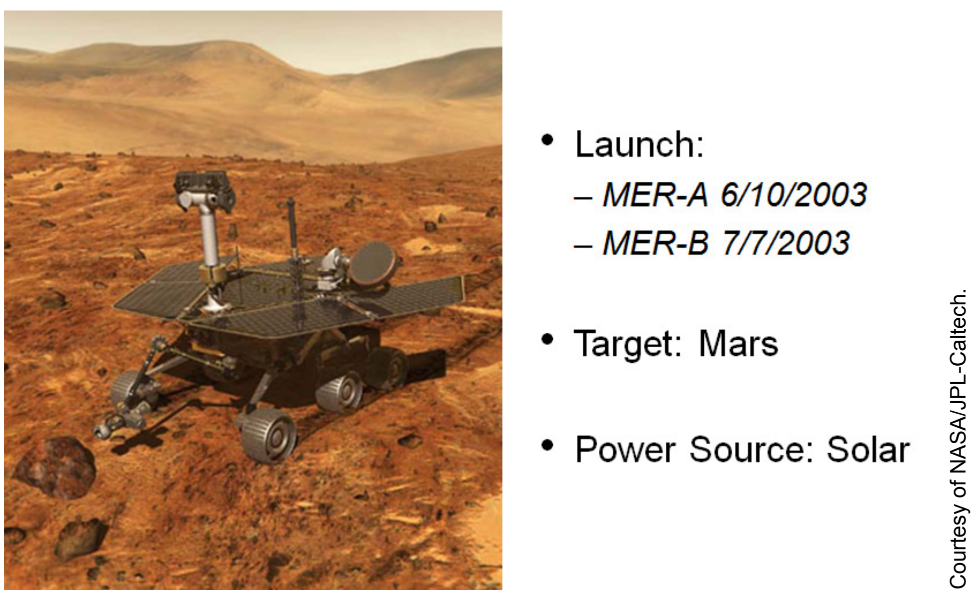


Figure 5. Mars Exploration Rover (MER)[2].

[2] Image Credit: NASA/JPL-Caltech, https://mars.nasa.gov/mer/gallery/artwork/rover3browse.html

MER Case Study Notes

- The solar panels restricted landing site choices. They needed +/- 5 degrees from the equator to receive reasonable power.

- Dust on solar panels limits MER lifetime. MER goes into hibernation mode in the winter, since there is not enough power generated.

- Thermal overnight is a really big issue, as solar panels need to make sure batteries are charged during the day to make sure enough heat can be generated at night. RTG could have provided heat overnight and allowed some instruments to take measurements at night, but the size of the RTG prohibited use on MER.

3.4 Europa Clipper

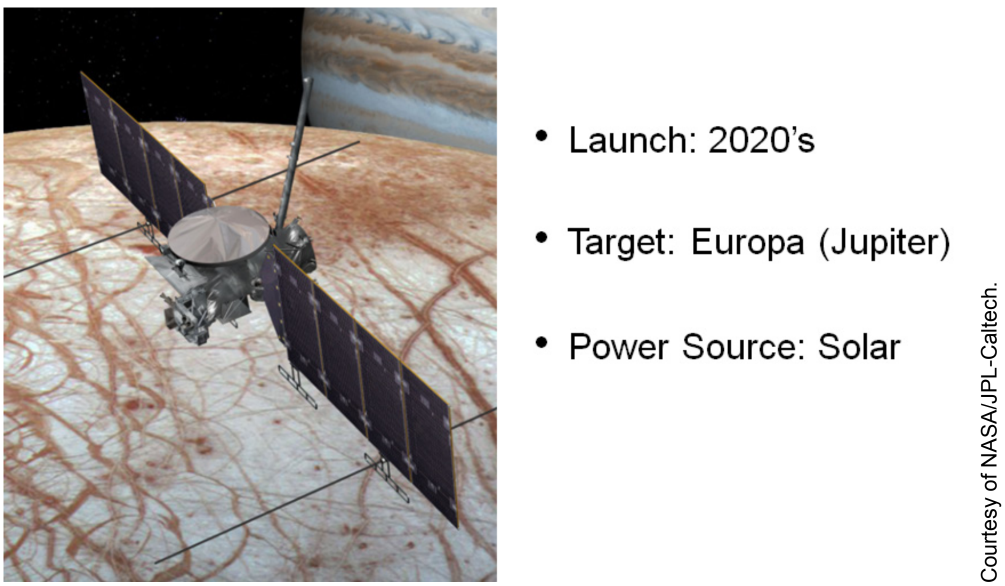


Figure 6. Europa Clipper[3].

Europa Clipper Case Study Notes (RPS to Solar)

- There was a formal trade study of 5 options: MMRTG, eMMRTG, 1 MMRTG + Solar, 1 eMMRTG + Solar, and Solar – Rigid Flat Panel (RFP). This trade study was performed after solar power was determined to be feasible. The trade study had previously screened out ASRG and ROSA. There was no direction or influence of the project from the outside. It was determined that GPHS-RTG would have been ideal, given power-level and lifetime considerations.

- The rationale for options included best combinations. All combinations seemed feasible for a 2022 launch, with 2024 as backup. RTG was good for heat considerations. Solar was easy to control with more known delivery schedule and scalability.

[3] Image Credit: NASA/JPL-Caltech, https://www.jpl.nasa.gov/missions/web/europa_full.jpg

- Other considerations included MMRTG (degradation, micrometeoroid susceptibility, and fuel production for 2022 launch) and eMMRTG (development schedule for 2024 launch).

- A comprehensive system-by-system review was performed to determine whether RPS was a requirement to enable or significantly enhance development. In all cases, it was found that solar power would not be an impediment to successful development.

- Figure 7 provides the summary of the power source trade study. The trade study considered technical, cost, schedule, reliability, and risk. It used both quantitative and qualitative assessments. Quantitative factors were weighted and scored. A sensitivity analysis was performed. The overall choice was Solar-RFP.

- Figure 8 provides the criteria and weighting approach for this power source trade study. Figure 9 provides the quantitative results summary.

- Policy considerations are also important and were considered in the Europa Clipper trade

  - National Policy:

    "The United States shall develop and use space nuclear power systems where such systems safely enable or significantly enhance space exploration or operations capabilities."
    National Space Policy of the United States of America, June 28, 2010

  - Institutional Policy:

    "The design shall avoid the use of nuclear materials (e.g. RHUs, RTGS) unless they are essential to mission viability or overwhelmingly cost-effective."
    JPL Design Principles, Section 4.1.8, "Use of Nuclear Materials"

As an additional exercise, the weighting criteria used in the Europa Clipper (Figure 9) was revisited. Using these criteria, if cost and schedule categories were eliminated, the results show that eMMRTG would have been the preferred candidate.

Summary of Power Source Trade

MMRTG

Pros:

- Minimal power system maintenance
- Low intersystem dependencies

Cons:

- High degradation over mission life
- High probability of loss of unmitigated MMRTG due to MMOD
- High cost
- Long lead time; does not support current launch date

Solar

Pros:

- Lower cost; short lead time supports current launch date
- Significant technology leverage from Juno
- Lower degradation over mission life; supports extended mission
- High MMOD probability, low consequence

Cons:

- Requires low temp qualification to support eclipse durations
- High system interdependence
- Impacts on pointing / stability performance

Figure 7. Europa Clipper Power Source Trade Study summary.

Criteria and Weighting Approach

- Criteria proposed by WG and approved by FSET
- PM/SCM provided weights for major categories, totaling 100%
- WG Suballocated weights to criteria
  - Averaged System Design impact criteria

Category	Weight
Technical	**30%**
Mass Margin	5%
Power Margin - Prime Mission	5%
Power Margin - Extended Mission	0%
System Design Impacts	10%
Design/Implementation Complexity	
Fault Management Complexity	
I&T and ATLO Complexity	
Operations Complexity	
Precision Pointing/Stability Impact	
EELV+ SLS Compatibility	
Design Principle Compliance	
Thermal Control Option Space	
Bioburden Impact	
Contamination	
Payload FOV	
Plume impingement	
IPR Radar Interference	
EMI	
Magnetic Cleanliness	
Spacecraft Charging	
Non-grav forces impacts	
Radiation Source (neutrons)	
Robustness	5%
Venus Hot/Jupiter cold compatibility	
Load Handling	
Part/Materials Radiation Susceptibility	
PP Sterilization (DHMR, VPHP) Compatibility	
Flexibility to Accommodate Changes	5%
Ease of scaling	
Accommodation of potential future requirements	
Accommodation of selected vs assumed payloads	
Trajectory, number of flyby's, eclipse times, power margin in extended mission, etc	

Category	Weight
Cost	**20%**
Source Cost (incl Launch Appv Eng)	
Launch Site Processing related to power source	
Technology Maturation (Project funded)	
Operations Cost related to power source	
Launch Vehicle Cost related to power source	
Schedule	**20%**
Life Test/Qualification	6%
Power Source Total Procurement Schedule	10%
Integration & Test	4%
Reliability	**10%**
Source Reliability	2%
Failure/Degradation Characteristics	2%
Human Safety	1%
TAYF Exceptions and Mitigations	1%
Deployment/Articulation Reliabilty	2%
MMOD Sensitivity	2%
Risk	**20%**
Technology Risk (consequence - likelihood)	5%
Life Cycle Cost Risk	5%
Schedule Risk	5%
Risk due to Multiple/Unknown LVs	5%
Weighted Total	**100%**

Figure 8. Europa Clipper Criteria and Weighting Approach for Power Source Trade Study.

Quantitative Results Summary

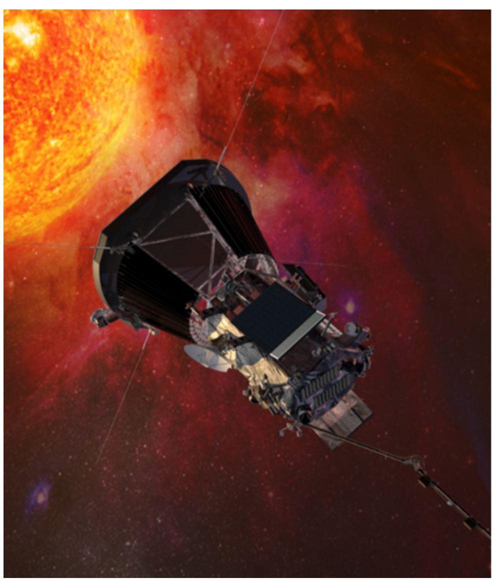
I8 Overall Results						
(blue) = Best; (red) = Worst		MMRTG	eMMRTG	1 MMRTG + Solar	1 eMMRTG + Solar	SA- RFP
Category	Weight	Weighted Score	Weighted Score	Weighted Score	Weighted Score	Weighted Score
Technical	30%	211	249	149	168	157
Cost	20%	20	20	80	80	180
Schedule	20%	44	80	128	50	160
Reliability	10%	61	81	52	52	57
Risk	20%	35	65	140	80	140
Weighted Total	100%	371	495	549	430	694

Solar is the clear winner and MMRTG is the last choice

- Additional technical complexities of solar are offset by slower and controllable degradation, lower cost and shorter schedule, less cost and schedule risk, and a favorable trend in technical risk
- Simplicity and reliability of nuclear sources are offset by high degradation rate and MMOD vulnerability (MMRTG) as well as the need for qualification, high cost, non-viable schedule, and cost/schedule risks (MMRTG and eMMRTG).
- Hybrids tend to get the best of both worlds in cost, schedule and risk, but the worst of both worlds in technical and reliability

Figure 9. Europa Clipper Quantitative Results Summary for Power Source Trade Study.

3.5 Parker Solar Probe (PSP)



- Launch: 2018
- Target: Sun
- Power Source: Solar

Courtesy of NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute.

Figure 10. Parker Solar Probe[4].

[4]Image Credit: Johns Hopkins University Applied Physics Laboratory, https://www.nasa.gov/sites/default/files/thumbnails/image/observingsunposter.jpg

Parker Solar Probe Case Study Notes (RPS to Solar)

- Initial PSP concepts at JPL and then at APL used RPS. The designers wanted to be able to go over the Sun's poles. They used Jupiter flyby – single 14-hour pass at 4 solar radii, with 5-year Jupiter transit.

- The APL PSP concept required 365 Watts. GPHS-RTG was not available, MMRTG was in development (engineering unit existed), and ASRG looked too far down the line.

- In 2007, the SMD AA mandated that the cost be cut to 70% of current cost. It was presumed that nuclear was too expensive and that savings could only be achieved with solar. It was also a concern that RTG would not be available.

- The study to meet the mandate only looked at solar concepts. The decision was to use existing technology and figure out how to cool the subsystem.

- Going solar required a trajectory change, from flying over the Sun's poles to orbiting the equator. The PSP concept orbited around Venus, down to 9.8 solar radii. It was determined that the new orbit met all the science goals.

- Numerous design features were implemented to accommodate solar power. Solar arrays were lowered as the spacecraft gets closer to the Sun to reduce power generation. Water was pumped under the solar arrays to actively cool them. Two giant radiators were placed behind the solar shield to cool the solar arrays, and a concentrator was laid over the solar arrays.

- The solar arrays significantly complicated spacecraft thermal and GN&C.

- The PSP was able to remove "dunce cap" solar shield, since not going as close to the Sun with solar.

- RTG would have significantly reduced the mission complexity. It would have eliminated solar array cooling system and fault management to deal with hot and cold when near to and far from the Sun, respectively.

- There were fewer launch opportunities with solar. The delay of 2015 launch pushed launch to 2018.

- In 2007, it was decided that RPS would not be used due to lack of plutonium, though the rationale was not explicit. APL originally baselined MMRTGs. The SMD AA provided direction to develop the PSP concept without RPS. Work on multiple Venus flybys done for very early mission concepts was rediscovered. The limitation was that it did not allow for flying over the poles to get latitudinal variation. The PSP ended up with a 9.86 solar-radii close approach: The spacecraft does not get as close to the Sun, but it gets more observation time at an acceptable distance, since the redesigned mission does not require flying out to Jupiter (4.5-year transit).

- Not going as close to the Sun lessened the worry about the dust environment and improved the thermal concern. For thermal control, it did not need the primary thermal shield of the original concept; the secondary thermal shield was sufficient.

- Venus flybys also allow for greater mission design flexibility.

3.6 Europa Lander

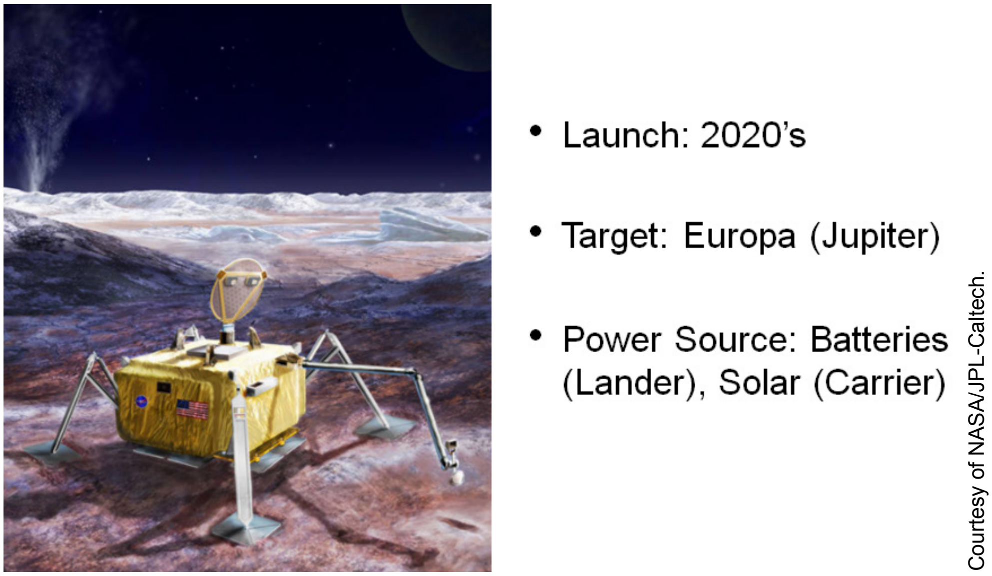


Figure 11. Europa Lander[5].

<u>Europa Lander Case Study (Trade Study Exploration)</u>

- This study performed a broad review of options for the both the carrier and the lander.

- The lander requires all-propulsive landing due to lack of atmosphere. There is a desire to keep mass at a minimum. Either MMRTG or eMMRTG were considered viable options, but there were issues of mechanical packaging due to size. The operating environment presented challenges. There was concern regarding a melting cryogenic surface creating unstable footing, since the MMRTG produces 2 kW of thermal energy. For planetary protection, the requirements were extremely stringent. NASA HQ planetary protection assumed that one germ to the surface would result in contamination of subsurface ocean. There was concern for radiation dose impact on potential indigenous organisms. It was assumed that the RPS concept was 1 MMRTG with batteries to support peak power. Solar concept was a non-starter. The array, which was twice the size of previous largest landed array, would only provide a couple of watts.

- The carrier’s use of MMRTG would have provided significant mass savings. Per policy requirement, it was hard to argue that RPS would ‘enable or significantly enhance’ capabilities. Solar was demonstrated by Juno and planned for Europa Clipper.

- Cost was an issue. There were numerous factors: accommodation, integration, NEPA compliance, and SLS certification. The cost impacts included: SLS certification of \$20M-\$30M and a power subsystem delta cost of ~\$200M, and the MMRTG lander would have total cost impact of ~\$500M.

- The MMRTG had the benefit of increased surface lifetime. The limiting factor then becomes the radiation exposure of the carrier. A three to six-month surface stay would require development of

[5]Image Credit: NASA/JPL-Caltech, https://www.nasa.gov/feature/nasa-receives-science-report-on-europa-lander-concept

hardened electronics. The MMRTG would enable long-term science (e.g., seismometry), and the planned science could be met with batteries.

- Batteries were the choice for the lander. The primary reason was planetary protection. There was concern about making sure RPS could meet stringent contamination requirements and not harm potential indigenous life. NASA SMD made the final decision. The project provided results of trades and provided some suggestions, and tried to stay even-handed and objective.

3.7 Juno

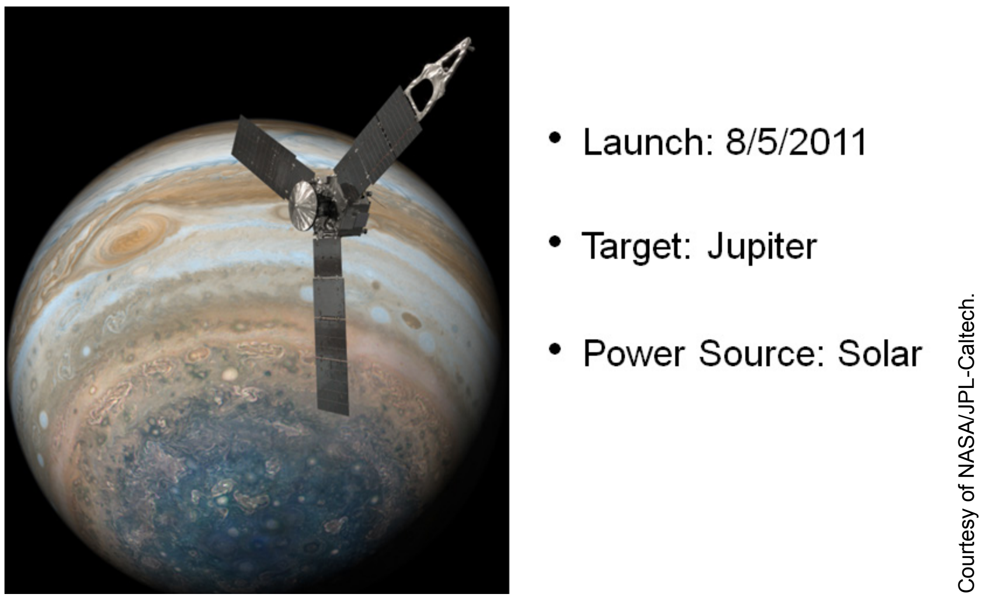


Figure 12. Juno[6]

<u>Juno Case Study Notes (Trade Space Exploration)</u>

- The choice would have been to use RPS if it truly had been available. No older types were available, as they were committed to other missions. The last GPHS-RTG went to New Horizons. Solar was made to work.

- There was no compromise in science with solar, but it complicated the design. There was a need to stay Sun-pointing the majority of the time. The design stayed simple and did not go with articulated arrays. Batteries were changed to support when pointing away from the Sun. Downlinking often required pointing away from the Sun. The spacecraft became larger due to the solar arrays. It required solar array development at additional cost. LILT testing was performed. Higher efficiency cells were examined, but the decision was to go with the best cells in the lot, which was costly. There was also concern with radiation and solar cell degradation, since the available lifetime is still not fully known.

- The overall cost of using solar was in line with given RPS cost ($20M). It was planned to lower to 14 days orbit for prime science. The propulsion system was exhibiting anomalous behavior so did not lower, but stayed in the 53-day orbit. The mission can still complete all science, but it is taking longer. It must deal with the eclipse period, which would not be an issue with RPS.

[6] Image Credit: NASA/JPL-Caltech, https://www.nasa.gov/sites/default/files/thumbnails/image/pia21771.jpg

Instruments cannot see Jupiter's whole orbit. This is the tradeoff of power versus instrument pointing. If solar could not have supported the science, the mission would likely have proposed RPS to get the full science—and then see what would happen with the selection, as opposed to proposing solar with reduced science.

- The mission conducted in-depth discussions on the selection of the power source for five missions: MSL, PSP, Europa Clipper, Europa Lander, and Juno.

- The mission also looked at the impact to operations between similar missions using different power sources: MMRTG for MSL versus solar power for MER.

- Case studies show that unique mission design and planned science have the greatest impact on the selection of RPS. There does not appear to be a common reason for the choice of power source among the case studies.

- RPS performs well when assessed for reliability and technically enabling qualities.

- Policy, however, limits use of RPS. National policy allows it where "safely enables" or "significantly enhances." JPL policy restricts to "essential for mission viability or overwhelmingly cost effective."

- Planetary protection of the operational environment was the determining factor for Europa Lander.

- Cost was also a primary variable that lead to RPS not being selected, given that cost can be prohibitive. This was the primary decision choice for Europa Clipper, and influenced PSP and Europa Lander.

- The availability and schedule risk also affected the selection. Headquarters redirected PSP away from RPS over concerns of lack of plutonium. Juno preferred RPS, but was concerned the delay of RPS development would have deemed the mission not selectable.

- Missions like MSL, however, are enabled by RPS, as solar powered systems do not meet requirements due to sunlight or thermal constraints.

4. MOE Discussion

4.1 MOE Introduction

The purpose of a potential MOE is to provide guidance, and ideally, would provide a clear indication that RPS is the best design choice for a given mission. The MOE should also be objective (i.e., there should not be weighting factors or other subjective input). An MOE should also be traceable to its inputs. Assuming that the MOE is calculated based on multiple inputs, each input should be clearly defined and defensible, and it should be clear how each input is used in the final calculation. An MOE should also be as comprehensive as possible. It should include all aspects of technical performance as well as cost when providing guidance. This study provided two MOEs, one based on cost of the EPS subsystem and another science value metric for comparison of the science merit of RPS versus solar missions.

4.2 Cost of RPS versus Solar MOE

One consideration is to look at the typical solar array EPS subsystem cost versus an RPS-based EPS subsystem cost, given a similar set of power and mission lifetime requirements. This study utilized collected data to develop EPS subsystem cost estimating relationships for solar and RPS subsystems. It used data to calculate the ratio of cost of solar to RPS to see if there is a "dark green zone" where cost for RPS is less than solar (solar/RPS > 1 = dark green). This study also looked at varied end-of-mission (EOM) power requirements for varied mission lifetimes. The results show influence of cost and performance on affordability of RPS.

The underlying calculations were:

- Solar array beginning-of-life (BOL) power requirement based on EOM power requirement

$$Solar\ BOL\ Required = \frac{EOM}{(1 - \%Annual\ Degradation)^{Mission\ Life\ years} * \left(\frac{1}{Distance\ from\ Sun\ in\ AU}\right)^2}$$

- RPS BOL requirement based on EOM requirement

$$RPS\ BOL\ Required = \frac{EOM}{(1 - \%Annual\ Degradation)^{(Mission\ Life\ years\ +\ 3\ years\ prior\ to\ fueling)}}$$

- EPS subsystem cost derived from collected dataset
  - Function of solar array size and EOM power
  - Full cost of power generation and distribution
- RPS cost based on the historical sources
  - Sources normalized to FY17$M
  - Total EPS cost estimated, based on ratio of total EPS to RPS cost from data set
  - Does not, however, consider other potential savings on spacecraft (e.g., thermal), as that is mission and spacecraft design specific

RPS Cost for Projected 2025 Mission (FY15 $)

RPS Type and Quantity	Cost to Fuel & Launch System ($M)	Additional Cost for LSP ($M)	Additional Cost ($M)	Total ($M)
RPS & RHU Missions				
1 MMRTG	55	22	0	77
2 MMRTG	72	22	0	94
3 MMRTG	95	22	0	117
1 MMRTG + RHU (Quantity < 43)[1]	55	22	2[2]	79
2 MMRTG + RHU (Quantity < 43)[1]	72	22	2[2]	96
3 MMRTG + RHU (Quantity < 43)[1]	95	22	2[2]	119
1 MMRTG + RHU (Quantity >43 and < 190)	55	22	31[3]	108
2 MMRTG + RHU (Quantity>43 and < 190)	72	22	31[3]	125
3 MMRTG + RHU (Quantity >43 and < 190)	95	22	31[3]	148
RHU ONLY Missions				
Quantity < 43	22	19	2	43
Quantity >43 and < 190	22	19	31[3]	72

1. Currently, 43 units are available. All are near 0.89 W_{th}
2. Cost to prepare and use RHUs
3. A new campaign would be needed for new RHUs. ($31M) The costs for that campaign are included in the above numbers.

For Planning And Discussion Purposes Only
This Data Does Not Constitute A Commitment By NASA Or DOE

2

Figure 13. RPS cost for a projected 2025 mission (FY15 $).

Possible Future RPS

- enhanced Multi-Mission Radioisotope Thermoelectric Generator (e-MMRTG)
  - Retrofit the MMRTG with higher efficient thermoelectric (TE) couples
  - Midway through Technology Maturation Phase
- Next Generation RTG (Next Gen)
  - In-house TE maturation efforts
  - RFI followed by RFP for system concept and technology maturation long-pole plan
  - Initial planning phase
- Dynamic RPS (DRPS)
  - SOA assessment - complete
  - Requirements definition - complete
  - Multiple industry, multiple conversion technology contracts – imminent

Parameter	MMRTG	eMMRTG	Next Gen	DRPS
TRL	9	3	1-3	3-4
Potential Flight Readiness Target Date	2009	2022	2028	2026
P_0 - BOL (We)	110	148	400-500	200-500
Efficiency - $P_0/Q*100$ (%)	5.50%	7.40%	10-14%	20-25%
Specific Power - P_0/m (We/Kg)	2.4	3.3	6-8	4-6
Q - BOL (Wth)	2000	2000	4000	1000-2000
Average annual power degradation, r (%/yr)	4.8%	2.5%	1.9%	1.3%
P_{BOM} - $P=P_0*e^{-rt}$ (We)	95	137	375-470	195-485
Fueled storage life, t (years)	3			
P_{EODL} - $P=P_0*e^{-rt}$ (We)	49	80	290-360	170-420
Flight Design Life, t (yrs)	14			
Design Life, t (yrs)	17			
Allowable Flight Voltage Envelope (V)	22-36	22-34		
Planetary Atmospheres (Y/N)	Y	Y	N	Y

15

Figure 14. RPS performance data.

Figure 13 provides the RPS cost for a projected 2025 mission. Figure 14 displays RPS performance data taken from “Outer Solar System: Many Worlds to Explore,” Outer Planets Assessment Group (OPAG) View of Decadal Survey Progress, May 2017. The cost and performance parameters for RPS systems were obtained from these sources for use in the MOE. Costs were inflated to FY17$M for use in the MOE.

There are six steps in the calculation of the MOE:

1. Calculate solar array BOL power requirement based on EOM power requirement & mission lifetime.

$$Solar\ BOL\ Required = \frac{EOM}{(1 - \%Annual\ Degradation)^{Mission\ Life\ years} * \left(\frac{1}{Distance\ from\ Sun\ in\ AU}\right)^2}$$

2. Calculate RPS BOL requirement based on EOM requirement & lifetime.

$$RPS\ BOL\ Required = \frac{EOM}{(1 - \%Annual\ Degradation)^{(Mission\ Life\ years\ +\ 3\ years\ prior\ to\ fueling)}}$$

3. Calculate solar array size based on BOL requirement.

4. Calculate solar-based EPS subsystem cost based on solar array size and EOM power.

5. Calculate RPS-based EPS subsystem cost based on # RTGs needed.

6. Calculate the ratio of solar-based to RPS-based EPS subsystem

   - Solar/RPS < 0.8 = light green
   - Solar/RPS > 1 = dark green
   - 0.8 < x < 1 = medium green

Figure 15 and Figure 16 present the results of the MOE comparison for the MMRTG RPS system. For each of the following figures, the top left quadrant provides an overview of the calculations of the MOE. The other three quadrants give the results of the MOE at various planetary destinations, where the power requirement is varied on the vertical axis and the mission lifetime is varied on the horizontal axis. These calculations pertain to orbiter missions, unless noted otherwise. Figure 15 shows the results of the MOE at Mars, Jupiter, and Saturn. As can be seen by the presence of only the light and medium-green regions at all three destinations, this indicates that MMRTG only begins to be somewhat cost effective at Saturn versus solar. Figure 16 provides the results for a Lunar Lander, and at Uranus and Neptune. As seen here, MMRTG is not cost effective for a Lunar Lander, but is overwhelmingly cost effective at Uranus and Neptune.

Similarly, Figure 17 and Figure 18 present the results of the MOE comparison for the Enhanced MMRTG or eMMRTG RPS system. Figure 17 shows the results of the MOE at Mars, Jupiter, and Saturn. Here, the results are similar to that of the MMRTG, but, with the improved performance of the eMMRTG, more darker green regions begin to appear at Saturn. Figure 18 provides the results for a Lunar Lander, and at Uranus and Neptune. The results seen here are the same as that of the MMRTG, with the eMMRTG not being cost effective for a Lunar Lander, but overwhelmingly cost effective for orbiter missions at destinations beyond Saturn.

- Ratio represents cost of solar EPS subsystem to RPS cost
- Ratio Key
  - *Solar/RPS < 0.8 = Light Green*
  - *Solar/RPS > 1 = Dark Green*
  - *0.8 < x < 1 = Medium Green*
- Result shows when RPS is more cost effective
- RPS cost from New Frontiers AO4
- Cost (FY17$M) = $80M for 1 unit, $98M for 2, $122M for 3 and $21M for each additional unit
- BOL Power = 110 W
- Degradation = 4.8% per year

Mars @ 1.5 AU

Mission Lifetime (Years)

EOM Power Required (W)	3	4	5	6	7	8	9	10	11	12
250	0.08	0.08	0.08	0.08	0.08	0.08	0.07	0.07	0.07	0.07
500	0.07	0.07	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.06
750	0.06	0.06	0.06	0.06	0.06	0.06	0.05	0.06	0.05	0.05
1000	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05
1250	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05
1500	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05
1750	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.04
2000	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04

Note: Results above are for a Mars orbiter, not lander

Jupiter @ 5.2 AU*

Mission Lifetime (Years)

EOM Power Required (W)	3	4	5	6	7	8	9	10	11	12
400	0.29	0.26	0.27	0.28	0.28	0.26	0.26	0.27	0.25	0.26
450	0.29	0.29	0.27	0.27	0.28	0.26	0.27	0.27	0.25	0.26
500	0.28	0.29	0.29	0.27	0.28	0.28	0.27	0.27	0.26	0.26
550	0.30	0.28	0.29	0.29	0.28	0.28	0.27	0.27	0.28	0.26
600	0.30	0.30	0.28	0.29	0.30	0.28	0.29	0.27	0.28	0.27
650	0.32	0.30	0.31	0.29	0.29	0.28	0.29	0.27	0.28	0.27
700	0.31	0.32	0.30	0.31	0.29	0.30	0.29	0.27	0.28	0.27
750	0.30	0.31	0.30	0.30	0.29	0.30	0.28	0.29	0.28	0.27

Europa Clipper Case

Juno Case

Galileo Case

* Note: Some of these solar solutions may not be feasible

Saturn @ 9.6 AU*

Mission Lifetime (Years)

EOM Power Required (W)	3	4	5	6	7	8	9	10	11	12
100	0.43	0.44	0.45	0.46	0.47	0.48	0.49	0.50	0.51	0.52
200	0.61	0.63	0.64	0.66	0.68	0.59	0.60	0.62	0.63	0.65
300	0.75	0.77	0.68	0.70	0.72	0.74	0.76	0.69	0.71	0.72
400	0.85	0.77	0.79	0.81	0.83	0.77	0.79	0.81	0.75	0.77
500	0.83	0.85	0.88	0.81	0.84	0.86	0.81	0.83	0.78	0.80
600	0.90	0.92	0.86	0.89	0.91	0.86	0.88	0.84	0.86	0.83
700	0.95	0.98	0.92	0.95	0.90	0.93	0.88	0.85	0.87	0.84
800	1.00	0.95	0.97	0.93	0.95	0.92	0.89	0.91	0.88	0.86

* Note: Some of these solar solutions may not be feasible

Figure 15. MOE results: MMRTG – Case 1 of 2.

- Ratio represents cost of solar EPS subsystem to RPS cost
- Ratio Key
  - *Solar/RPS < 0.8 = Light Green*
  - *Solar/RPS > 1 = Dark Green*
  - *0.8 < x < 1 = Medium Green*
- Result shows when RPS is more cost effective
- RPS cost from New Frontiers AO4
- Cost (FY17$M) = $80M for 1 unit, $98M for 2, $122M for 3 and $21M for each additional unit
- BOL Power = 110 W
- Degradation = 4.8% per year

Lunar Lander

Mission Lifetime (Years)

EOM Power Required (W)	3	4	5	6	7	8	9	10	11	12
100	0.09	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
200	0.09	0.09	0.09	0.09	0.09	0.08	0.08	0.08	0.08	0.08
300	0.09	0.09	0.08	0.08	0.08	0.08	0.08	0.07	0.07	0.07
400	0.08	0.07	0.08	0.08	0.08	0.07	0.07	0.07	0.06	0.07
500	0.07	0.07	0.08	0.07	0.07	0.07	0.07	0.07	0.06	0.06
600	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.06	0.06	0.06
700	0.07	0.07	0.07	0.07	0.07	0.07	0.06	0.06	0.06	0.06
800	0.07	0.07	0.07	0.07	0.07	0.06	0.06	0.06	0.06	0.06

Uranus @ 19.2 AU*

Mission Lifetime (Years)

EOM Power Required (W)	3	4	5	6	7	8	9	10	11	12
100	1.46	1.50	1.54	1.58	1.62	1.67	1.71	1.76	1.80	1.85
125	1.81	1.86	1.91	1.96	2.01	2.06	1.68	1.72	1.77	1.82
150	2.15	2.21	1.79	1.84	1.89	1.95	2.00	2.05	2.11	2.17
175	1.97	2.03	2.08	2.14	2.20	2.26	2.32	2.02	2.07	2.13
200	2.25	2.31	2.37	2.44	2.50	2.18	2.24	2.30	2.36	2.43
225	2.52	2.59	2.25	2.31	2.38	2.44	2.51	2.58	2.30	2.36
250	2.36	2.43	2.50	2.56	2.63	2.71	2.41	2.48	2.55	2.62
275	2.59	2.67	2.74	2.82	2.51	2.58	2.65	2.72	2.80	2.54

* Note: Solar array solutions are currently not feasible for Uranus

Neptune @ 30.1 AU*

Mission Lifetime (Years)

EOM Power Required (W)	3	4	5	6	7	8	9	10	11	12
100	3.47	3.56	3.66	3.76	3.87	3.97	4.08	4.20	4.31	4.43
125	4.32	4.44	4.56	4.69	4.82	4.95	4.02	4.13	4.25	4.37
150	5.16	5.31	4.31	4.43	4.55	4.68	4.81	4.95	5.08	5.23
175	4.75	4.88	5.02	5.16	5.30	5.45	5.60	4.87	5.01	5.15
200	5.42	5.57	5.73	5.89	6.05	5.26	5.41	5.56	5.72	5.88
225	6.09	6.26	5.44	5.60	5.75	5.91	6.08	6.25	5.57	5.72
250	5.72	5.88	6.04	6.21	6.39	6.57	5.85	6.01	6.18	6.35
275	6.29	6.46	6.64	6.83	6.08	6.25	6.43	6.61	6.79	6.16

* Note: : Solar array solutions are currently not feasible for Neptune

Figure 16. MOE results: MMRTG – Case 2 of 2.

- Ratio represents cost of solar EPS subsystem to RPS cost
- Ratio Key
  - *Solar/RPS < 0.8 = Light Green*
  - *Solar/RPS > 1 = Dark Green*
  - *0.8 < x < 1 = Medium Green*
- Result shows when RPS is more cost effective
- RPS cost from New Frontiers AO4
- Cost (FY17\$M) = \$80M for 1 unit, \$98M for 2, \$122M for 3 and \$21M for each additional unit
- BOL Power = 148 W
- Degradation = 2.5% per year

Mars @ 1.5 AU

Mission Lifetime (Years)

EOM Power Required (W)	3	4	5	6	7	8	9	10	11	12
250	0.11	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
500	0.10	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
750	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.08	0.08	0.08
1000	0.09	0.08	0.08	0.09	0.09	0.09	0.08	0.08	0.08	0.08
1250	0.09	0.08	0.08	0.09	0.09	0.08	0.08	0.08	0.08	0.08
1500	0.09	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
1750	0.09	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
2000	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08

Note: Results above are for a Mars orbiter, not lander

Jupiter @ 5.2 AU*

Mission Lifetime (Years)

EOM Power Required (W)	3	4	5	6	7	8	9	10	11	12
400	0.34	0.35	0.35	0.36	0.37	0.38	0.39	0.40	0.40	0.41
450	0.37	0.38	0.39	0.40	0.41	0.36	0.37	0.38	0.39	0.40
500	0.41	0.36	0.37	0.38	0.39	0.40	0.41	0.42	0.43	0.44
550	0.39	0.39	0.40	0.41	0.42	0.43	0.39	0.40	0.41	0.42
600	0.42	0.43	0.44	0.39	0.40	0.41	0.42	0.43	0.44	0.46
650	0.39	0.40	0.41	0.42	0.43	0.44	0.46	0.42	0.43	0.44
700	0.42	0.43	0.44	0.45	0.42	0.43	0.44	0.45	0.46	0.47
750	0.45	0.41	0.42	0.43	0.44	0.45	0.46	0.43	0.44	0.45

Europa Clipper Case

Juno Case

Galileo Case

* Note: Some of these solar solutions may not be feasible

Saturn @ 9.6 AU*

Mission Lifetime (Years)

EOM Power Required (W)	3	4	5	6	7	8	9	10	11	12
100	0.53	0.54	0.55	0.57	0.58	0.59	0.61	0.62	0.64	0.65
200	0.77	0.79	0.81	0.83	0.86	0.88	0.90	0.92	0.95	0.97
300	0.89	0.91	0.93	0.96	0.98	1.01	1.04	1.06	1.09	1.12
400	0.98	1.01	1.04	1.06	1.09	1.12	1.15	1.18	1.21	1.25
500	1.22	1.08	1.11	1.14	1.17	1.20	1.24	1.27	1.30	1.34
600	1.26	1.29	1.32	1.20	1.23	1.27	1.30	1.34	1.37	1.41
700	1.29	1.32	1.36	1.39	1.28	1.32	1.35	1.39	1.43	1.46
800	1.31	1.35	1.38	1.42	1.46	1.36	1.39	1.43	1.47	1.51

* Note: Some of these solar solutions may not be feasible

Figure 17. MOE results: eMMRTG – Case 1 of 2.

- Ratio represents cost of solar EPS subsystem to RPS cost
- Ratio Key
  - *Solar/RPS < 0.8 = Light Green*
  - *Solar/RPS > 1 = Dark Green*
  - *0.8 < x < 1 = Medium Green*
- Result shows when RPS is more cost effective
- RPS cost from New Frontiers AO4
- Cost (FY17\$M) = \$80M for 1 unit, \$98M for 2, \$122M for 3 and \$21M for each additional unit
- BOL Power = 148 W
- Degradation = 2.5% per year

Lunar Lander

Mission Lifetime (Years)

EOM Power Required (W)	3	4	5	6	7	8	9	10	11	12
100	0.11	0.11	0.11	0.11	0.11	0.11	0.12	0.12	0.12	0.12
200	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
300	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.10
400	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09
500	0.09	0.09	0.09	0.08	0.08	0.08	0.08	0.08	0.09	0.09
600	0.09	0.09	0.09	0.09	0.09	0.08	0.08	0.08	0.08	0.08
700	0.08	0.08	0.08	0.09	0.09	0.09	0.08	0.08	0.08	0.08
800	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08

Uranus @ 19.2 AU*

Mission Lifetime (Years)

EOM Power Required (W)	3	4	5	6	7	8	9	10	11	12
100	1.82	1.87	1.91	1.97	2.02	2.07	2.13	2.19	2.24	2.31
125	2.25	1.86	1.91	1.96	2.01	2.06	2.12	2.18	2.24	2.30
150	2.15	2.21	2.27	2.33	2.40	2.46	2.53	2.60	2.67	2.74
175	2.50	2.57	2.64	2.71	2.78	2.86	2.94	3.02	3.10	3.19
200	2.84	2.92	3.00	3.08	3.17	3.26	3.35	3.44	3.53	3.63
225	3.19	3.28	3.37	3.46	3.55	2.89	2.97	3.05	3.13	3.22
250	3.53	2.87	2.95	3.03	3.12	3.20	3.29	3.38	3.47	3.57
275	3.07	3.15	3.24	3.33	3.42	3.52	3.61	3.71	3.82	3.92

* Note: Solar array solutions are currently not feasible for Uranus

Neptune @ 30.1 AU*

Mission Lifetime (Years)

EOM Power Required (W)	3	4	5	6	7	8	9	10	11	12
100	4.31	4.43	4.56	4.68	4.81	4.94	5.08	5.22	5.37	5.51
125	5.37	4.44	4.56	4.69	4.82	4.95	5.09	5.23	5.37	5.52
150	5.16	5.31	5.45	5.61	5.76	5.92	6.09	6.26	6.43	6.61
175	6.01	6.18	6.35	6.53	6.71	6.90	7.09	7.29	7.49	7.70
200	6.86	7.05	7.25	7.45	7.66	7.87	8.09	8.32	8.55	8.79
225	7.71	7.92	8.14	8.37	8.61	6.99	7.19	7.39	7.60	7.81
250	8.55	6.95	7.14	7.34	7.55	7.76	7.98	8.20	8.43	8.67
275	7.43	7.64	7.85	8.07	8.30	8.53	8.77	9.02	9.27	9.53

* Note: : Solar array solutions are currently not feasible for Neptune

Figure 18. MOE results: eMMRTG – Case 2 of 2.

- Ratio represents cost of solar EPS subsystem to RPS cost
- Ratio Key
  - *Solar/RPS < 0.8 = Light Green*
  - *Solar/RPS > 1 = Dark Green*
  - *0.8 < x < 1 = Medium Green*
- Result shows when DRPS is more cost effective
- DRPS cost estimate from June Zakrajsek
- Cost (FY17$M) = $107M for 1 unit and $25M for each additional unit
- BOL Power = 500 W
- Degradation = 1.3% per year

Mars @ 1.5 AU

Mission Lifetime (Years)

EOM Power Required (W)	3	4	5	6	7	8	9	10	11	12
250	0.10	0.10	0.10	0.10	0.11	0.11	0.11	0.11	0.11	0.11
500	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.12	0.12
750	0.13	0.14	0.14	0.14	0.14	0.14	0.12	0.12	0.12	0.12
1000	0.13	0.13	0.14	0.14	0.14	0.14	0.14	0.14	0.15	0.15
1250	0.15	0.16	0.14	0.14	0.14	0.14	0.14	0.14	0.15	0.15
1500	0.15	0.15	0.15	0.16	0.16	0.16	0.14	0.14	0.15	0.15
1750	0.15	0.15	0.15	0.15	0.16	0.16	0.16	0.16	0.16	0.15
2000	0.16	0.17	0.17	0.15	0.15	0.16	0.16	0.16	0.16	0.17

Note: Results above are for a Mars orbiter, not lander

Jupiter @ 5.2 AU*

Mission Lifetime (Years)

EOM Power Required (W)	3	4	5	6	7	8	9	10	11	12
400	0.46	0.47	0.48	0.49	0.50	0.51	0.53	0.54	0.55	0.56
450	0.51	0.52	0.53	0.43	0.44	0.45	0.47	0.48	0.49	0.50
500	0.44	0.45	0.46	0.48	0.49	0.50	0.51	0.52	0.54	0.55
550	0.48	0.49	0.51	0.52	0.53	0.54	0.56	0.57	0.58	0.60
600	0.52	0.53	0.55	0.56	0.57	0.59	0.60	0.62	0.63	0.65
650	0.56	0.57	0.59	0.60	0.62	0.63	0.65	0.66	0.68	0.70
700	0.60	0.61	0.63	0.64	0.66	0.68	0.69	0.71	0.73	0.75
750	0.64	0.65	0.67	0.69	0.70	0.72	0.74	0.76	0.78	0.79

Europa Clipper Case

Juno Case

Galileo Case

* Note: Some of these solar solutions may not be feasible

Saturn @ 9.6 AU*

Mission Lifetime (Years)

EOM Power Required (W)	3	4	5	6	7	8	9	10	11	12
100	0.39	0.40	0.41	0.41	0.42	0.43	0.44	0.45	0.47	0.48
200	0.70	0.72	0.74	0.76	0.78	0.80	0.82	0.84	0.86	0.88
300	1.02	1.05	1.07	1.10	1.13	1.16	1.19	1.22	1.25	1.29
400	1.34	1.37	1.41	1.45	1.48	1.52	1.56	1.61	1.65	1.69
500	1.32	1.36	1.39	1.43	1.47	1.51	1.55	1.59	1.63	1.68
600	1.57	1.62	1.66	1.71	1.75	1.80	1.85	1.90	1.95	2.00
700	1.83	1.88	1.93	1.98	2.03	2.09	2.15	2.20	2.26	2.33
800	2.08	2.14	2.20	2.25	2.32	2.38	2.44	2.51	2.58	2.65

* Note: Some of these solar solutions may not be feasible

Figure 19. MOE Results: DRPS - Case 1 of 2.

- Ratio represents cost of solar EPS subsystem to RPS cost
- Ratio Key
  - *Solar/RPS < 0.8 = Light Green*
  - *Solar/RPS > 1 = Dark Green*
  - *0.8 < x < 1 = Medium Green*
- Result shows when DRPS is more cost effective
- DRPS cost estimate from June Zakrajsek
- Cost (FY17$M) = $107M for 1 unit and $25M for each additional unit
- BOL Power = 500 W
- Degradation = 1.3% per year

Lunar Lander

Mission Lifetime (Years)

EOM Power Required (W)	3	4	5	6	7	8	9	10	11	12
100	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
200	0.10	0.10	0.10	0.10	0.10	0.10	0.11	0.11	0.11	0.11
300	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.13
400	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.14	0.14	0.14
500	0.12	0.12	0.12	0.12	0.12	0.12	0.13	0.13	0.13	0.13
600	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.14	0.14
700	0.14	0.14	0.15	0.15	0.15	0.15	0.15	0.15	0.16	0.16
800	0.15	0.16	0.16	0.16	0.16	0.16	0.17	0.17	0.17	0.17

Uranus @ 19.2 AU*

Mission Lifetime (Years)

EOM Power Required (W)	3	4	5	6	7	8	9	10	11	12
100	1.33	1.36	1.40	1.44	1.47	1.51	1.56	1.60	1.64	1.68
125	1.64	1.69	1.73	1.78	1.83	1.88	1.93	1.98	2.03	2.09
150	1.96	2.01	2.06	2.12	2.18	2.24	2.30	2.36	2.42	2.49
175	2.27	2.33	2.39	2.46	2.53	2.60	2.67	2.74	2.82	2.89
200	2.58	2.65	2.73	2.80	2.88	2.96	3.04	3.12	3.21	3.30
225	2.90	2.98	3.06	3.14	3.23	3.32	3.41	3.50	3.60	3.70
250	3.21	3.30	3.39	3.48	3.58	3.68	3.78	3.89	3.99	4.10
275	3.53	3.62	3.72	3.83	3.93	4.04	4.15	4.27	4.39	4.51

* Note: Solar array solutions are currently not feasible for Uranus

Neptune @ 30.1 AU*

Mission Lifetime (Years)

EOM Power Required (W)	3	4	5	6	7	8	9	10	11	12
100	3.15	3.24	3.33	3.42	3.51	3.61	3.71	3.81	3.92	4.03
125	3.92	4.03	4.14	4.26	4.37	4.50	4.62	4.75	4.88	5.02
150	4.69	4.82	4.96	5.09	5.24	5.38	5.53	5.69	5.84	6.01
175	5.46	5.61	5.77	5.93	6.10	6.27	6.44	6.62	6.81	7.00
200	6.23	6.41	6.58	6.77	6.96	7.15	7.35	7.56	7.77	7.99
225	7.00	7.20	7.40	7.61	7.82	8.04	8.26	8.49	8.73	8.98
250	7.77	7.99	8.21	8.44	8.68	8.92	9.17	9.43	9.69	9.97
275	8.54	8.78	9.03	9.28	9.54	9.81	10.08	10.37	10.66	10.95

* Note: Solar array solutions are currently not feasible for Neptune

Figure 20. MOE results: DRPS Case 2 of 2.

Finally, Figure 19 and Figure 20 present the results for the DRPS case. Figure 19 shows the results of the MOE at Mars, Jupiter, and Saturn. Here, the results are also similar to that of the eMMRTG, but again, with the improved performance of DRPS, even more darker green regions begin to appear at Saturn. Figure 20 provides the results for a Lunar Lander, and at Uranus and Neptune. The results seen here for DRPS are the same as that of the MMRTG and eMMRTG, as it is not cost effective for a Lunar Lander, but overwhelmingly cost effective for orbiter missions at destinations beyond Saturn.

4.3 Landed Power Considerations

MOEs for lander cases are much more complicated, as cost is not always the primary consideration. For some landed missions, sunlight and temperature constraints necessitated by science landing requirements make RPS systems the only viable implementation choice. For landed missions, power is required when the surface is in shadow. Additionally, landed missions typically require additional power to meet system minimum heating requirements when the surface is in shadow. RPS can survive long periods of darkness and operate at all times, as opposed to solar-based systems that would need to operate in a low-power mode to conserve energy until the solar array could again start generating power.

4.4 Cost-Competitive RPS

Similarly, the MOE can also be used to calculate the cost required to make RPS cost competitive. The graph below gives the RPS cost required for an RPS-based EPS subsystem cost to be equal to a solar-based EPS subsystem at Jupiter or its moons. Note that this assumes NextGen RPS performance of 500 watts and 1.9% annual degradation. It is understood, however, that science requirements may still necessitate the need for an RPS-based system.

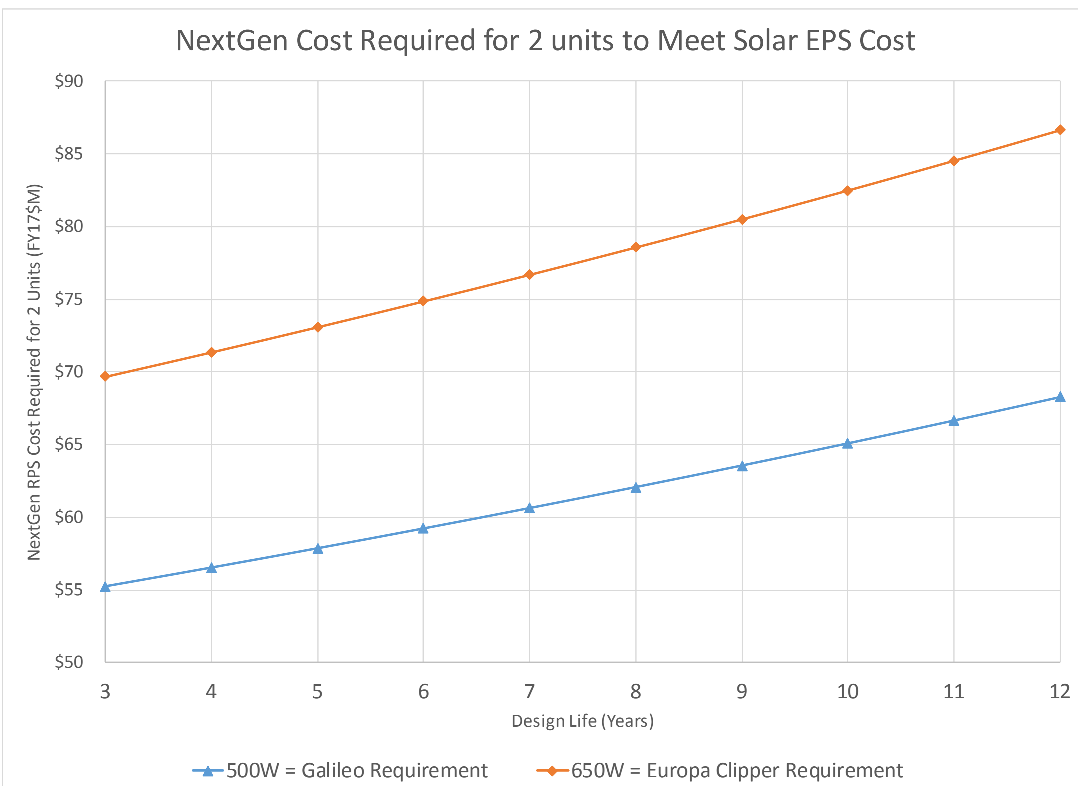


Figure 21. Cost-competitive RPS.

4.5 Assessment of Science Value

Quantifying science value can be a very difficult and subjective task. Preferably, it would somehow be quantified per dollar spent. The difficulty is in the determination of how science value be measured. Total quantity of data is different for different instrument types. Is an instrument that generates more data inherently more valuable? The number of images does not pertain to non-imaging instruments. Should one consider the number of published papers? Also, other subjective criteria cannot be easily quantified (e.g., number of "significant" findings).

The approach used here to determine science value is to use "instrument-months." This methodology has been used in two previous studies assessing the cost-effectiveness of small satellite and Category 3 missions.[7,8] Science data return can be represented by the number of instruments on a mission multiplied by the number of months the instrument operated. This assumes all instruments are included to answer specific scientific questions and therefore are of equal merit, although it is understood that this may not always be true. Instrument duration acts as surrogate for quantity and depth of information gathered.

Figure 22 shows a comparison of the instrument-months for each mission with the RPS missions colored blue, and the solar missions colored orange. For all RPS missions, the total instrument months is 13,249, while the solar missions total 6,403 instrument months.

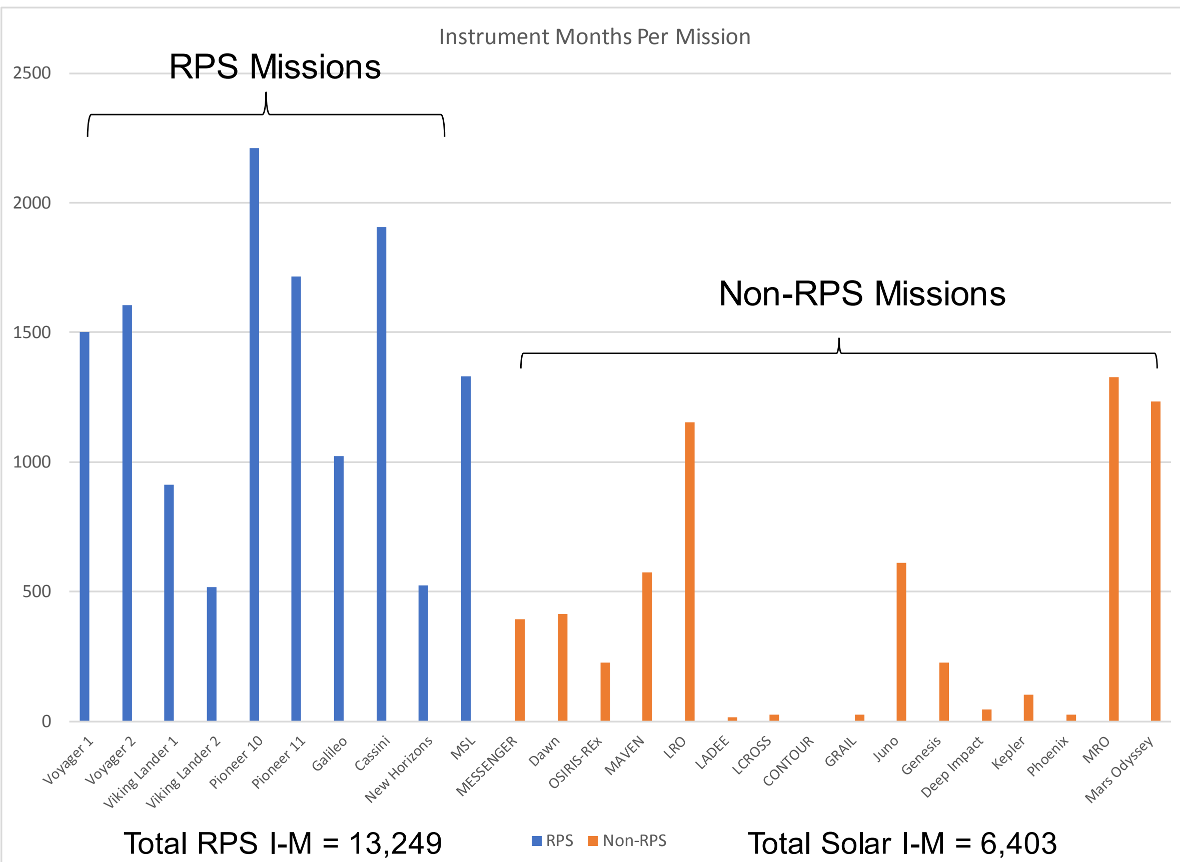


Figure 22. Science value instrument months comparison.

[7] "Evaluating Small Satellites: Is The Risk Worth It?", 1999 Small Satellite Conference.
[8] "Assessing the Benefits of NASA Category 3, Low Cost Class C/D Missions", 2013 IEEE Aerospace Conference.

To look at the overall cost-effectiveness of RPS and solar missions, Science Mission Cost-Effectiveness (SMCE) is used. The equations are shown in Figure 23, and the steps are described herein: Divide instrument-months by cost, calculate mission-by-mission numbers for individual, comparison, calculate class numbers for RPS versus non-RPS class comparison.

$$SMCE = \frac{I*t}{TMC}$$

- I = number of instruments flown
- t = time (in months) of instrument operation
- TMC = total mission cost

$$Class\ SMCE = \frac{\sum_{j=1}^{n} i_j * t_j}{\sum_{j=1}^{n} tmc_j}$$

- N= number of missions
- I_j = number of instruments flown on the jth spacecraft
- T_j = time (in months) of instrument operation on the jth spacecraft
- Tmc_j = total mission cost for the jth spacecraft

As an example, the steps for calculating the instrument-months and SMCE for the Mars Reconnaissance Orbiter (MRO) mission are as follows:

- MRO has 8 instruments operating during its lifetime
- MRO was transitioned to a stable orbit and began science operations in November of 2006 (est. 11/15/2006)
- MRO is still operating, after several extensions past its primary mission, and assumed to stop operating at the end of FY20 (i.e., 9/30/2020) at which point it will become primarily a communications relay for other Mars missions
  - This leads to an operating duration of the instruments of 166 months
  - Given its 8 instruments, the instrument month calculation would be: 8 instruments times 166 months = 1328 instrument-months
- MRO cost was $1,028 RY$M from launch to operations through FY20. Inflating to FY17$M results in total of $1,274M FY17$M.
- SMCE is total I-M divided by total cost

Comparing results for RPS (10) and non-RPS (16) missions show that the average number of instrument-months per mission is higher for RPS (i.e., more science per mission), and the SMCE is similar. The average instrument-months per mission is 1656 for RPS missions versus 400 for non-RPS missions. RPS missions typically enable a larger spacecraft with multiple instruments over a much longer operating time, thereby increasing the instrument-months over non-RPS missions. SMCE for all RPS missions, however, is 0.60 instrument-months per FY17$M versus 0.59 instrument-months per FY17$M for non-RPS missions. Table 5 shows the SMCE summary results.

Table 5. SMCE Summary Results

Mission Type	Average Instrument-Months	Class Science Mission Cost-Effectiveness
RPS	1656	0.60 I-M/$M
Non-RPS	400	0.59 I-M/$M

Figure 23 shows the detailed results behind these calculations. Missions in which no data was taken due to a mission failure are included as zero instrument-months, while the cost is included in the calculation for the total mission class calculation. Sample return missions include ground-based investigations after return for a planned number of years; these investigations are treated in the same manner as space-borne instrument-months. Data collected by in-situ instruments for flyby missions (i.e., Pioneer, Voyager) substantially influence the instrument-months calculation.

Summary RPS Missions		FY17$M	Number of	
Mission	I-M	LCC	Instruments	
Voyager 1 & 2	3,106	$ 2,482	11	
Viking Landers 1&2	1,428	$ 3,740	12	
Pioneer 10	2,212	$ 524	12	
Pioneer 11	1,716	$ 524	13	
Galileo	1,023	$ 5,654	11	
Cassini	1,908	$ 4,915	12	
New Horizons	525	$ 971	7	
MSL	1,331	$ 3,423	11	
Total	13,249	$ 22,233	SMCE =	0.60
Average IM/mission	1,656			
Ulysses	2,160	Too many contributions to cost		

* Note: Ulysses was not included since life cycle cost couldn't be calculated due to significant foreign contributions

Summary Non-RPS Missions		FY17$M	Number of	
Mission	I-M	LCC	Instruments	
MESSENGER	392	$ 650	8	
Dawn	415	$ 636	5	
OSIRIS-REx	227	$ 1,068	5	
MAVEN	576	$ 731	8	
LRO	1,152	$ 844	8	
LADEE	15	$ 299	3	
LCROSS	27	$ 107	9	
CONTOUR	-	$ 216	4	Failure
GRAIL	24	$ 539	1	
Juno	610	$ 1,301	10	
Genesis	228	$ 416	3	
Deep Impact	45	$ 474	3	
Kepler	104	$ 793	1	
Phoenix	25	$ 579	5	
MRO	1,328	$ 1,274	8	
Mars Odyssey	1,235	$ 845	6	
Total	6,403	$ 10,773	SMCE =	0.59
Average IM/mission	400			

Figure 23. SMCE detailed results.

5. Conclusion and Recommendations

This study was conducted to better understand the decisionmaking process behind choosing RPS or solar power systems for planetary spacecraft. Based on the analysis of data collected, in general, EPS cost appears higher for RPS systems than for solar systems. Through case studies, it appears that unique mission design and planned science have the greatest impact on the selection of RPS. Among five separate cases, there was no common reason for the choice of power source; however, primary decision factors included: cost, availability of RPS, and planetary protection. One prominent example is the Mars Science Laboratory (MSL) mission, which has been enabled by RPS, as solar powered systems did not meet mission requirements due to sunlight and thermal constraints. MOE analysis shows that RPS is most cost effective for outer planet (to Saturn and beyond) orbiter missions. MOE analysis also shows that, even at a higher cost, RPS enables large missions with multiple instruments working over a long operating life—and therefore provides substantial science value. This MOE assessment also shows that science value for RPS is higher per mission. However, science mission cost-effectiveness of RPS versus solar is similar when looking at a large set of missions.

Although a substantial amount of cost data was found for this study, further details of that cost that allow for clearer interpretation of them are often desirable. To form a complete understanding of the cost impact to a mission from using an RPS power source, the delta cost to launch services should be clearly documented. As part of the data collection process, this study attempted to acquire the cost impact on launch services from having an RPS power source. However, this data could not be obtained, as it either was not available or was tied in with other costs and could not be isolated. The MOE analysis also provides insight into how RPS needs to be improved. Any new RPS system (whether NextGen, DRPS, or beyond) needs better performance (higher BOL and less degradation) and to be less expensive than MMRTG and eMMRTG. MOEs derived from this study could be further utilized to assess planetary targets to identify the ones where RPS is more enabling and/or cost effective. Targets could be assessed for cost, planetary protection, and other considerations. These could be used to identify the most reasonable RPS missions, and could generate a quick reference table to inform mission designers (effectively a "cheat sheet" for trade studies).

6. Acronyms

AA	Associate Administrator
AO	Announcement of Opportunity
APL	Johns Hopkins Applied Physics Laboratory
ASRG	Advanced Stirling Radioisotope Generator
BOL	Beginning of Life
CADRe	Cost Analysis Data Requirement
CDR	Critical Design Review
CONTOUR	COmet Nucleus TOUR
CRP	Constant Production Rate
DoD	Depth of Discharge
DOE	Department of Energy
DRPS	Dynamic RPS
EIS	Environmental Impact Statement
eMMRTG	Enhanced Multi-Mission Radioisotope Thermoelectric Generator
EOM	End of Mission
EPS	Electrical Power Subsystem
FY	Fiscal Year
GN&C	Guidance Navigation & Control
GPHS-RTG	General Purpose Heat Source-Radioisotope Thermoelectric Generator
GRAIL	Gravity Recovery and Interior Laboratory
GRC	Glenn Research Center
HQ	Headquarters
IEEE	Institute of Electrical and Electronics Engineers
I-M	Instrument Months
JPL	Jet Propulsion Laboratory
kW	kilowatt
LADEE	Lunar Atmosphere and Dust Environment Explorer
LCROSS	Lunar Crater Observation and Sensing Satellite
LILT	low-intensity low temperature
LRO	Lunar Reconnaissance Orbiter
LSEP	Lunar Surface Experiments Package
LSP	Launch Services Program
MAVEN	Mars Atmosphere and Volatile Evolution

MER	Mars Exploration Rovers
MESSENGER	MErcury Surface, Space Environment, Geochemistry, and Ranging
MGS	Mars Global Surveyor
MMOD	Micrometeoroids and Orbital Debris
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
MOE	measures of effectiveness
MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory
NAFCOM	NASA Air Force Cost Model
NASA	National Aeronautics and Space Administration
NEPA	National Environmental Policy Act
NextGen	Next Generation RTG
OPAG	Outer Planets Assessment Group
OSIRIS-Rex	Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer
PDR	Preliminary Design Review
PI	Principal Investigator
PSP	Parker Solar Probe
REMS	Rover Environmental Monitoring Station
RFP	Rigid Flat Panel
RHU	Radioisotope Heater Unit
ROSA	Roll-Out Solar Array
RPS	Radioisotope Power System
RTG	Radioisotope Thermoelectric Generator
S/C	Spacecraft
SLS	Space Launch System
SMCE	Science Mission Cost-Effectiveness
SMD	Science Mission Directorate
SNAP	Systems Nuclear Auxiliary Power
SOA	State of the Art
SRG	Stirling Radioisotope Generator
TE	Thermoelectric
TMC	Total Mission Cost
W	Watt