A Historical Look at Performance Parameters and Decision Criteria for Robotic Planetary Exploration Power System Selections

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Introduction

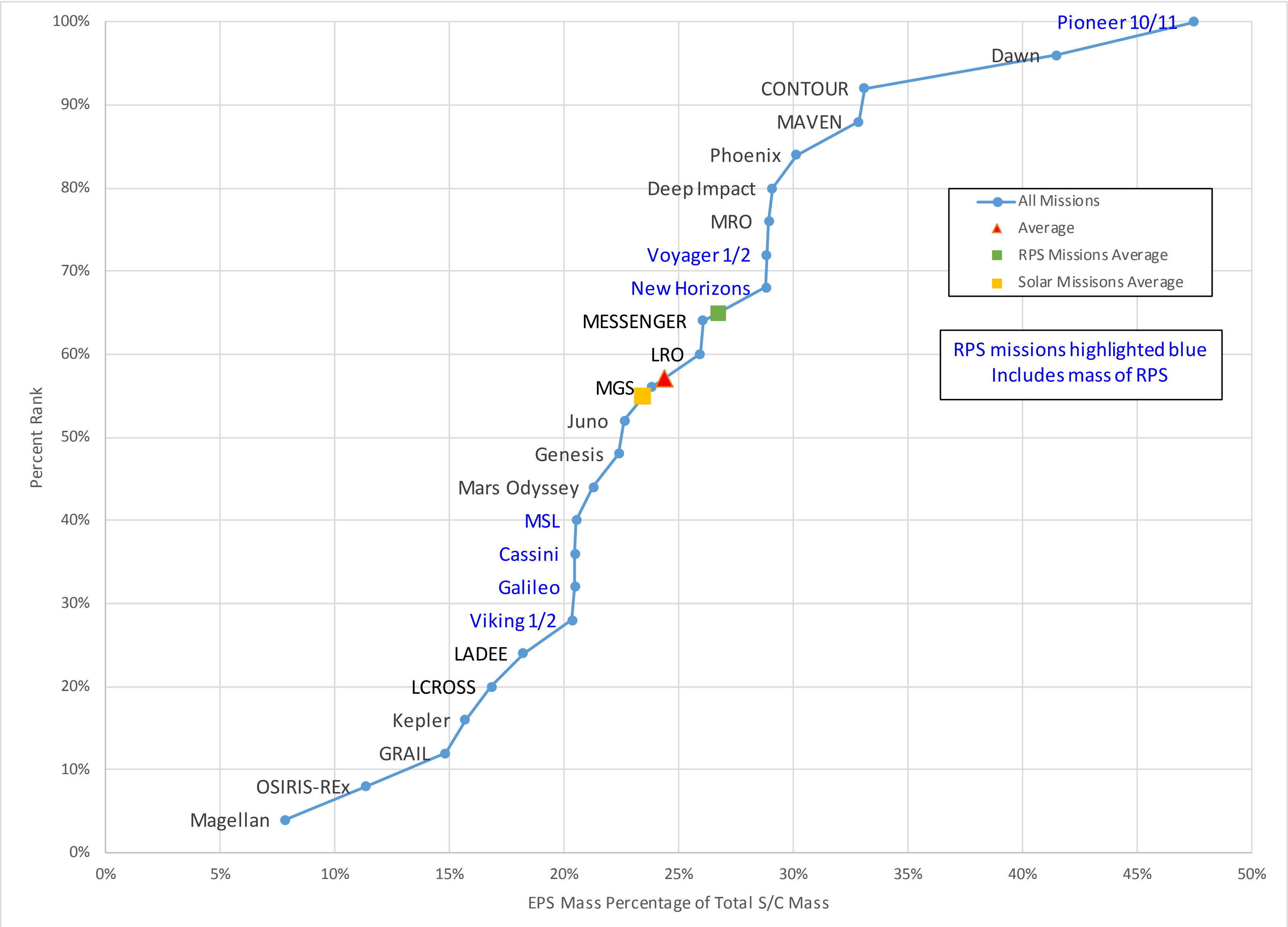
- NASA space missions have long employed Radioisotope Power Systems (RPS) and solar-based power generation architectures
- RPS have been used to enable or significantly enhance missions that venture deep into the solar system to distances from the sun which can make using solar architectures unfeasible
- The destination, however, is not the absolute factor of the determination of RPS or solar
  - *When baselining either RPS or solar architectures for a planetary mission, numerous factors must be considered, including the ability of meeting science requirements, ease of design integration, policy, schedule, cost and risk*

- In an effort to better understand the decision-making process and provide insight for potential future missions, the NASA RPS Program tasked The Aerospace Corporation (Aerospace) to study historical missions that used RPS and solar architectures
  - *Data was collected for a variety of RPS and solar missions to look for possible trends from the selected implementation*
  - *Mission case studies were also developed based on interviews with mission personnel who were responsible for defining the power architecture of their mission*
  - *A cost based Measures of Effectiveness (MoEs), informed by the collected data and case studies, was developed to serve as a tool in the decision-making process*

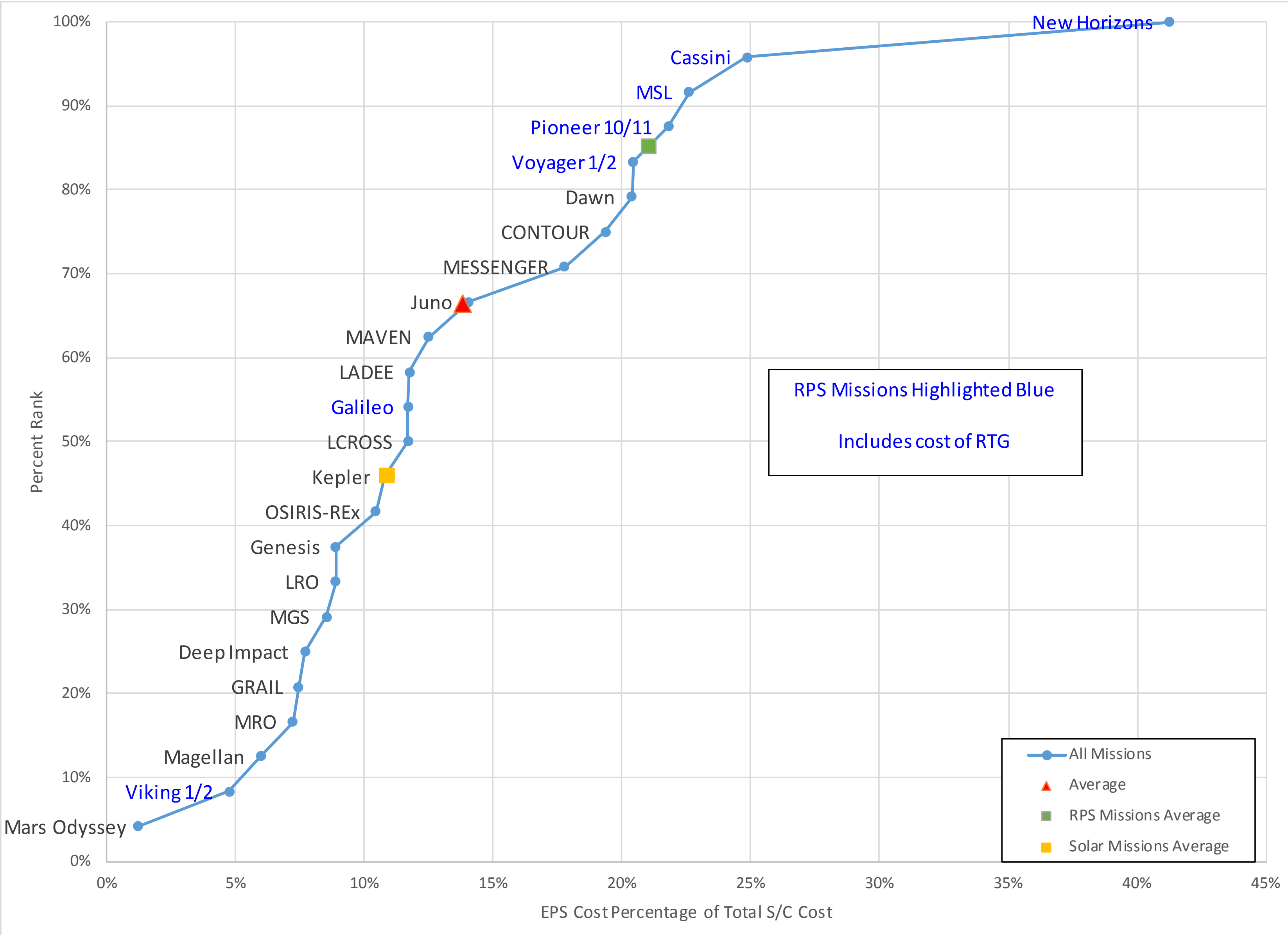
Data Collection Trends

- Data collection targeted
  - *18 solar missions launched primarily since 2000*
  - *16 RPS missions spanning all years*
- Data on some missions was limited
  - *Detailed cost data on Apollo RPS systems not available*
  - *Ulysses had many foreign contributions*
- Final core usable data includes 7 RPS mission and 18 solar missions
  - *RPS:*
    - Cassini, Galileo, MSL, New Horizons, Voyager, Pioneer, Viking
      - *Voyager 1/2, Pioneer 10/11, Viking 1/2 counted as 1 spacecraft each*
  - *Solar:*
    - CONTOUR, Dawn, Deep Impact, Genesis, GRAIL, Juno, Kepler, LADEE, LCROSS, LRO, Magellan, Mars Odyssey, MAVEN, MESSENGER, MGS, MRO, OSIRIS-REx, Phoenix
- Looked at variety of different slices of the data
  - *EPS mass as a percentage of spacecraft bus mass is comparable*
    - RPS = 27%, Solar = 23%
  - *EPS cost as a percentage of spacecraft bus cost is higher for RPS*
    - RPS = 21%, Solar = 11%
  - *EPS subsystem cost per EPS subsystem mass (FY17$M per kg) is higher for RPS*
    - RPS = $0.90, Solar = $0.20

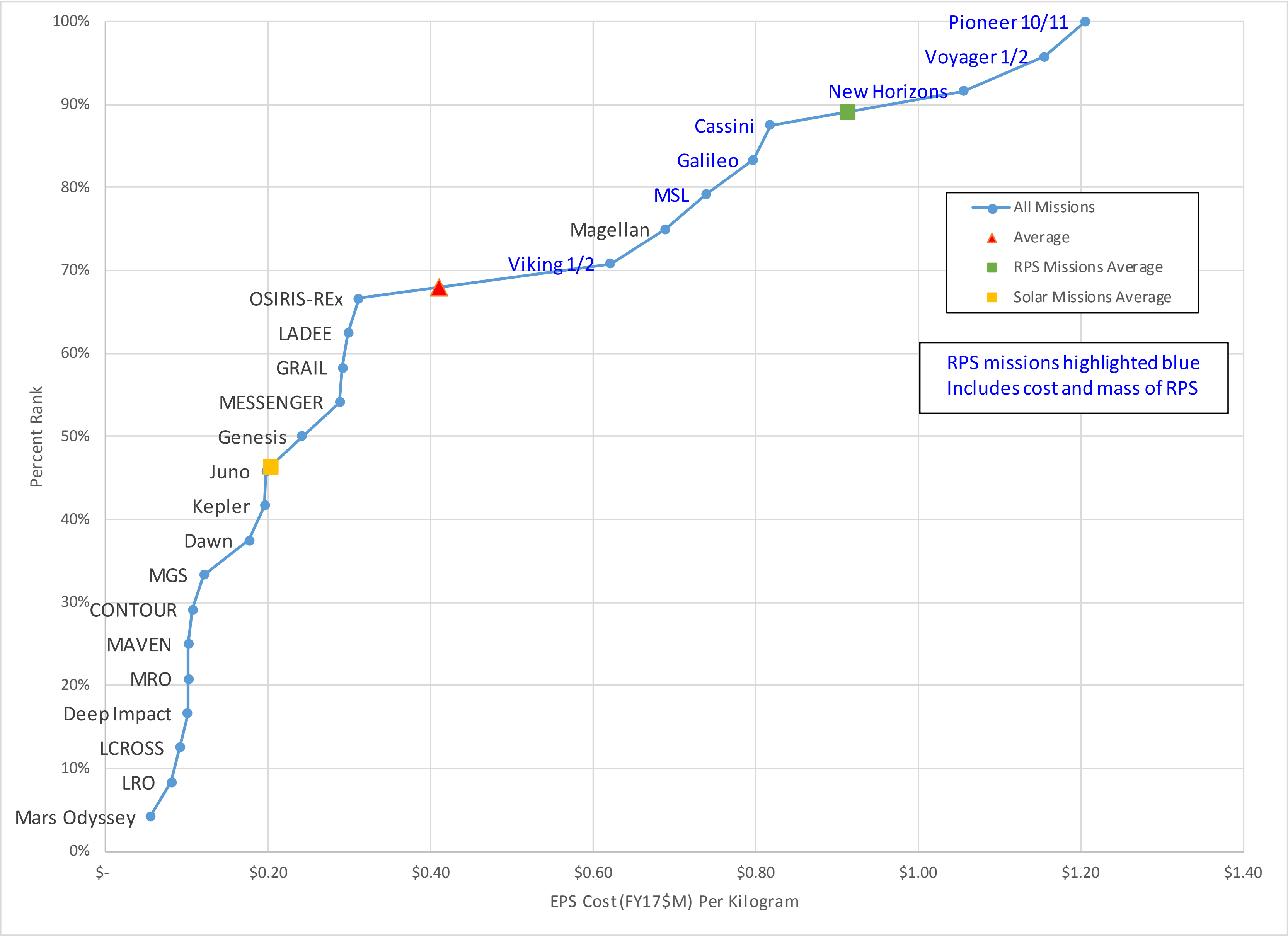
EPS Mass Percentage of Total Spacecraft Bus Mass



EPS Cost Percentage of Total Spacecraft Bus Cost



EPS Subsystem Cost per EPS Subsystem Mass



Case Studies Overview

- Mission case studies developed based on interviews with mission personnel who were responsible for defining the power architecture of their mission
  - *Discuss decision between RPS and solar power*
  - *Understand difference in operational complexity between RPS and solar power*
- Missions identified
    - Change from RPS to Solar: PSP and Europa Clipper
    - Change from Solar to RPS: MSL
    - Trade space exploration: Juno and Europa Lander
- For the choice of power source, the discussion was focused on the decision-making process and not any difficulties encountered during development as a result of the decision
- Case studies show that unique mission design and planned science have the greatest impact on the selection of RPS
  - *No 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 and cost and schedule are other major considerations*

Case Studies Results

Mission	Background	Decision criteria
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 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
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
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 • Further complicated by lengthened mission due to propulsion issue which includes more eclipse periods
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

MOE Overview

- Purpose of a potential MOE is to provide guidance
  - *Ideally would provide a clear indication that RPS is the best design choice for a given mission*
- Ideally the MOE should be objective
  - *i.e., there shouldn't be weighting factors or other subjective input*
- 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*
- MOE should also be as comprehensive as possible
  - *Should include all aspects of technical performance as well as cost when providing guidance*
- 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
- Utilized collected data to develop EPS subsystem cost estimating relationships for solar and RPS subsystems
- Used data to calculate ratio of cost of solar to RPS
  - *See if there is a "dark green zone" where cost for RPS is less than solar*
    - Solar/RPS > 1 = Dark Green
- Looked at varied EOM power requirements for varied mission lifetimes
- Results show influence of cost and performance on affordability of RPS

MOE Results: MMRTG Case

- 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	0.05	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 (650 W, 6 years: 0.29)
Juno Case (450 W, 6 years: 0.27)
Galileo Case (500 W, 8 years: 0.28)

* 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

MOE Results: eMMRTG Case

- 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 (650 W, 6 years: 0.42)

Juno Case (450 W, 6 years: 0.40)

Galileo Case (500 W, 8 years: 0.40)

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

Saturn @ 9.6 AU*

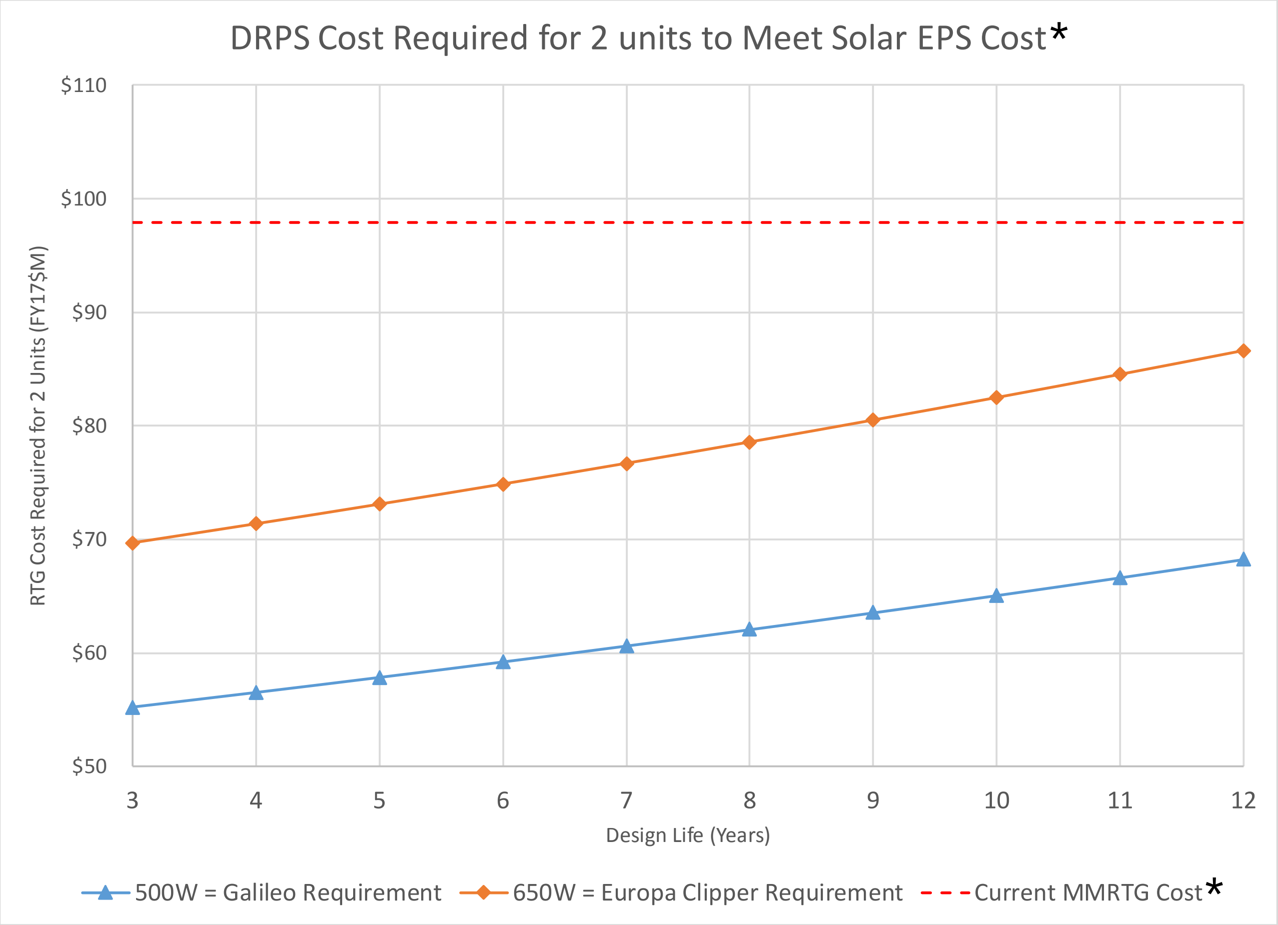
Mission Lifetime (Years)

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

Cost Competitive RPS

- Can use similar methodology as was used for the MOE to calculate cost required to make RPS cost competitive
- Graph below shows the RTG cost required to result in a RTG-based EPS subsystem cost equal to a solar-based EPS subsystem at Jupiter or its moons
  - *It is understood, however, that science value/requirements may necessitate the need for an RTG-based system*
- Assumptions
  - *Assumed DRPS performance of 500 Watts and 1.3% Annual Degradation*



*Note: Required DRPS cost and current MMRTG cost includes LSP cost

Summary

- Selection of RPS for a given mission depends on many factors including the ability of meeting science requirements, ease of design integration, policy, schedule, cost and risk
- Data collections shows that EPS subsystem cost is higher for RPS systems
- Case studies show that unique mission design and planned science have the greatest impact on the selection of RPS
  - *There doesn't seem to be a common reason for the choice of power source*
  - *Primary decision factors included: cost, availability of RPS and planetary protection*
- Missions like MSL are enabled by RPS as solar powered systems don't meet requirements due to sunlight or thermal constraints
- MOE assessment shows that, from a cost perspective, RPS only is primarily cost effective for Outer Planet orbiter missions (to Saturn and beyond)
- If the cost of RPS were reduced and performance enhanced beyond eMMRTG and DRPS, RPS systems could be more readily adoptable for a broader range of missions and enable more challenging missions