Solar Energy from Space:
A Decadal Revisit to the First International Assessment of Opportunities, Issues and Potential Pathways Forward

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Introduction

SG 3.31 Background

- During 2008-2011, the International Academy of Astronautics (IAA) Commission III implemented "*Space Solar Power: The First International Assessment of Space Solar Power*" (published in 2011), which was widely regarded as an important step forward in establishing the technical viability of the concept.
- Moreover, there is a long-standing "Power Committee" within the International Astronautical Federation (IAF), that organization which organizes the longest running series of meetings on the topic – e.g., a symposium at the International Astronautical Congress (IAC); the 2008-2011 IAA study was conduced in concert with the IAF Power Committee.
- A decade has passed since the initiation of the first IAA study of SSP …

through this New study, the IAA (through Commission III) to undertake a focused "decadal review and assessment" of the SSP concept for the purposes of accomplishing several important goals, described below.

SG 3.31 Planning

SG 3.31 Study Goals

- The overall goals of this study are to
  - ✓ evaluate what role solar energy from space might play in meeting the rapidly growing and evolving need for abundant and sustainable energy during the remainder of this century,
  - ✓ assess the technology options, readiness and risks associated with the SSP concept,
  - ✓ evaluate the range of novel SSP concepts that have emerged, and
  - ✓ update the international roadmap developed during the IAA study 10 year ago that might lead the realization of this visionary concept.
- Because significant advances in space solar power systems could have a profound and positive impact on human and robotic space exploration capabilities as well as a range of space applications, the study will also
  - ✓ assess such opportunities and update the earlier assessment of the potential for synergies between these benefits for space missions and SSP for terrestrial markets.
- Finally, there is a potential role that extraterrestrial resources might play in SSP architectures; the study will
  - ✓ attempt to identify these opportunities and assess potential connections between international government and commercial exploration programs (Moon, small bodies, etc.) now being undertaken and SSP

SG 3.31 Study Intermediate Goals

- Identification of relevant markets and applications for new energy sources—including both ultimate applications in terrestrial markets, as well as interim applications in space programs.
- Identification and evaluation of the technical options that may exist for solar energy from space to contribute to meeting global energy needs, focusing on the most-promising specific SSP concepts that have been identified.
- Identification and evaluation of the technical options that may exist for space solar power to contribute to ambitious government and commercial space mission concepts and markets.
- Evaluation of the impact of emerging space transportation options to enable SSP – particularly Earth-to-orbit (ETO) systems in development or operations (as of 2018-2021).
- Identification and evaluation of options for the utilization of extraterrestrial resources, in particular lunar and asteroid resources in future space solar power systems.
- Evaluate of progress toward appropriate SSPS architecture level figures-of-merit (identified during the 2008-2011 IAA study, and values of these that must be achieved in order for solar energy from space is to become economically viable for a range of terrestrial market opportunities and space applications.
- Preliminary identification of other issues and policy questions that would require resolution for SSPS to become a reality, with particular attention on spectrum allocation.
- Assessment of the technical feasibility, technological maturity and degree of difficulty in the above space solar power options.
- Formulation of a strategic approach to realizing the potential of energy from space – and one or more technical / programmatic international roadmaps implementing this strategy.
- Development of a summary report, documenting the results of the study and articulating the prospects for energy delivered from space to make a substantial contribution to satisfying future global needs

SG 3.31 Membership

Chair(s):

- John C. Mankins (M)
- *A co-chair may be identified at the IAA meetings in Fall 2019.*

Secretary:

- Haroon Oqab

Additional Members:

- Additional members, to be identified
- *HOWELL, Joe T. (to be invited)*
- *MIHARA, Shoichiro (to be invited)*
- *SCHROGL, Prof. Dr. Kai-Uwe (representing Commission 5; to be invited)*

Members:

- BARNHARD, Gary
- BRANDHORST, Henry Ph.D.
- CASH, Ian
- HOU, Xinbin
- JAFFE, Paul Ph.D.
- LI, Ming Ph.D. (M)
- MARZWELL, Neville I., Ph.D.
- PERINO, Maria Antonietta
- PIGNOLET, Guy
- SHERWOOD, Brent
- SWAN, Peter Swan (M)
- TANAKA, Koji Ph.D.
- GOPALASWAMI, Raghavan
- SUMMERER, Leopold
- VASILE, Massimiliano (Mx)

WORKING DISCUSSION

Major Changes since 2008-2011

- Terrestrial Solar Expansion
  - Massive expansion, globally
- New SSP Concepts
  - A variety of new concepts have emerged, and new versions of existing concepts…
- Low-Cost Launch
  - There has been a revolution in low-cost commercial launch
- Commercial Space / Development / Exploration
  - Similarly, because of the new prospects for the commercial development of space, there is now the real potential (within the foreseeable future) for space resources and in-space manufactured systems / sub-systems that could be integrated into future SPS assembly and maintenance markets.

Major Changes since 2008-2011
ACTIONS THAT WILL BE TAKEN BY THE SG

- Ground Solar
  - Consider how SSP can be integrated with ground solar / wind
- New Concepts
  - A comparative assessment of several new Solar Power Satellite (SPS) concepts that have emerged during the past 10 years or so -- including comparison to the best and/or most well-known systems concepts of the past (such as the 1979 SPS Reference System concept).
  - This comparative would include identifying the SPS concept, developing an engineering-focused description of the concept, assessment of the technologies required. JCM hopes that it would also include high-level analytical modeling (spreadsheet type) of the several concepts, so that there would some real technical work to be accomplished.
- Low-Cost Launch
  - The advent of low-cost commercial launch has stimulated a tremendous increase in activity related to the commercial development of cis-lunar space.
  - Such activities include mining of volatiles on the Moon, creation of products such as propellants, space settlement activities (e.g., agriculture, etc.), space tourism, and many more. All of these activities will require substantial and affordable new sources of energy if they are going to succeed.
- Commercial Space / Development / Exploration
  - Similarly, because of the new prospects for the commercial development of space, there is now the real potential (within the foreseeable future) for space resources and in-space manufactured systems / sub-systems that could be integrated into future SPS assembly and maintenance markets.

Selected SSP Architecture Options (1 of 2) Locations / Targets

- Earth
  - GEO (Geostationary and Geosynchronous) Earth Orbit
  - LEO Equatorial
  - LEO near-Equatorial
  - LEO Sun-Synchronous
  - MEO
  - MEO / Molniya
- Moon
  - Orbit
  - Surface-to-Surface SSP / WPT (Polar)
  - Libration Points
- Mars
  - Mars Surface Point-to-Point
  - Mars Synchronous Orbit for Mars Surface
  - Mars System Vicinity (e.g., Moons)
- Solar
  - Small Bodies Vicinity
- Main Belt Asteroids
- Others?

Selected SSP Architecture Options (1 of 2)
Locations / Targets - DETAIL

Location	~Solar Distance	~Insolation	"Shadowing"
Sun	0	63,000,000 W/m^2	N/A
Mercury	57,000,000 m	9,100 W/m^2	Frozen D/N
Venus	108,000,000 m	2,600 W/m^2	Perm. Overcast
Earth	149,000,000 m	1,370 W/m^2	~12/12 hours (Surface)
Moon	149,000,000 m	1,370 W/m^2	~14/14 days (Surface)
Mars System	227,000,000 m	590 W/m^2	~13/13 hrs (Surface)
M/B Asteroids	~400,000,000 m	140 W/m^2	Variable
Jupiter	~780,000,000 m	50 W/m^2	Variable
Saturn	~1,426,000,000 m	15 W/m^2	Variable
Uranus-Neptune	3,000-4,500 M km	2-4 W/m^2	Variable
Kuiper Belt/Pluto	~6,000 M km	~1 W/m^2	Variable

Selected SSP Architecture Options (2 of 2) Systems Concepts – A Sampling

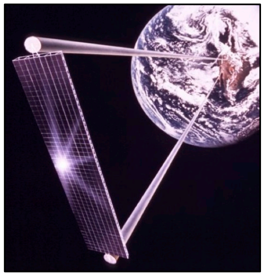
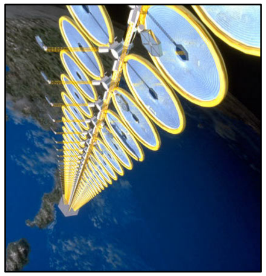
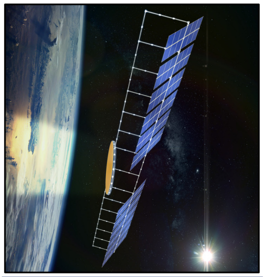
- SPS Reference System
  - c. 1979; US; DOE/NASA
- Multiple Array Central Transmitter Concept
  - c. 2018; South Korea / ROK; KARI
- Multiple-Array "POP" Concept
  - c. 2016; China; CAST / LI
- Cassiopeia
  - c. 2015-2016; UK; Cash
- Thin-Film Planar v1
  - c. 2014; US; NGT/CIT
- SPS-ALPHA
  - c. 2012 (Initial) - 2019 (Latest); US; Mankins

- Planar Tether Sandwich Concept
  - c. 2004; Japan; JAXA / Sasaki
- Sail Tower
  - c. 2004; Europe; ESA
- Linear Solar Pumped Laser
  - c. 2004; Japan; JAXA

- First Version SPS
  - c. 1968; US; Glaser
- SPS Feasibility Study
  - c. 1974; US; Glaser et al
- SPS Ref. System (+variants)
  - c. 1979; US; DOE/NASA

- Integrated Symmetrical Concentrator
  - c. 2000; US; NASA / SERT
- Sun Tower
  - c. 1996; US; NASA (Fresh Look Study)
- Reflect Array
  - c. 1996; US; NASA (Fresh Look Study)
- Solar Disc
  - c. 1996; US; NASA (Fresh Look Study)
- Modular Laser "POP" Tower
  - c. 1996; US; Aerospace Corporation / NASA (Penn/ Fresh Look Study)
- Reflector Sandwich SPS
  - c. 1995; Japan; Kobe University / Kaya

SPS Concepts Comparison (Group I)

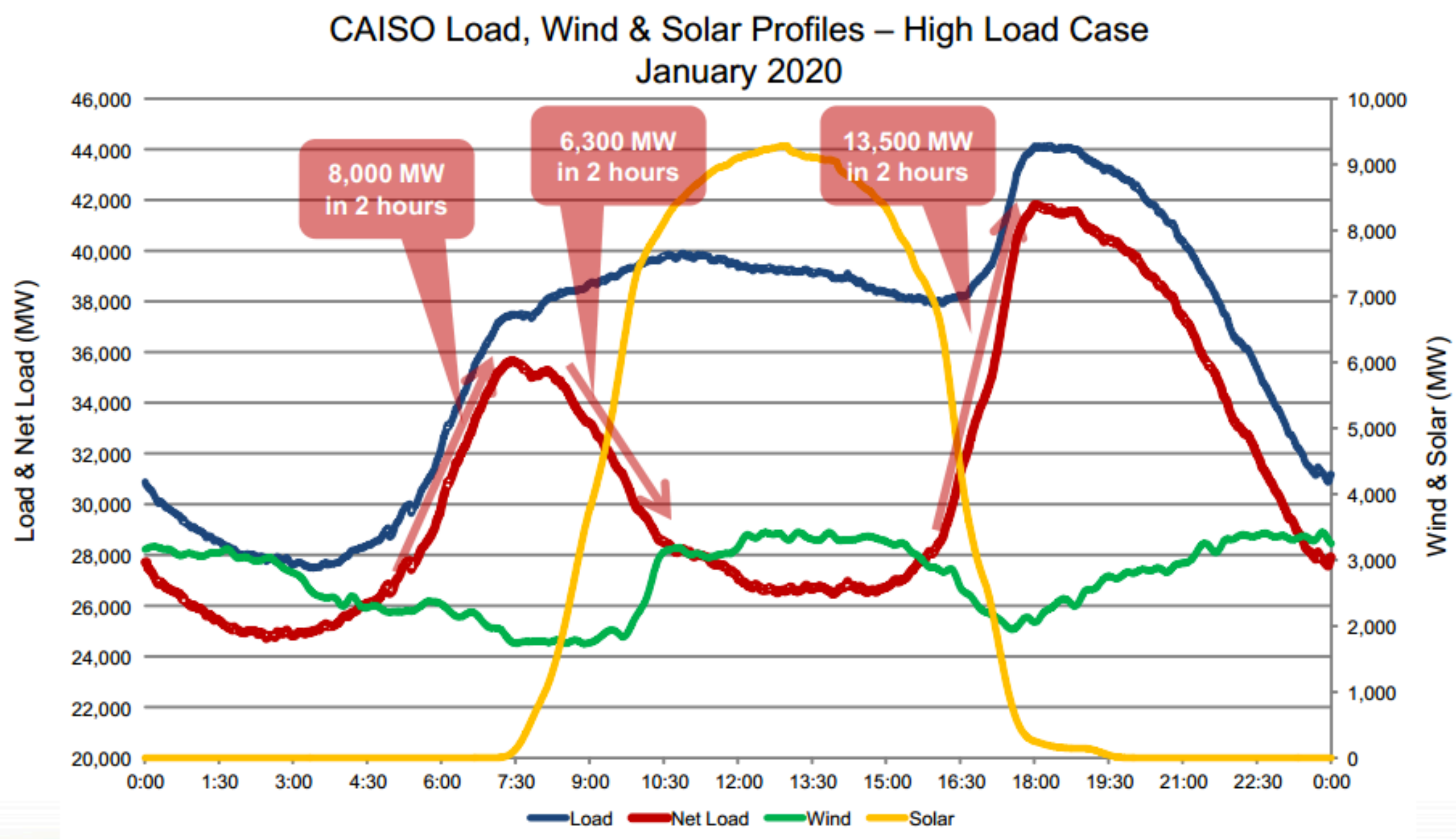




Design Feature	1979 SPS Reference	1997 NASA Sun Tower / 2004 ESA Sail Tower	2015 CAST SPS	c. 2004 JAXA Tether Sandwich SPS	2015 NG/CIT Thin Film SPS	TBD
Wireless Power	Microwave, Tube (e.g., Gyrotron)	Microwave, Solid State	Microwave, Solid State	Microwave, Solid State	Microwave, Solid State on Thin-Film	TBD
Energy Conversion	PV (eg, Si)	PV (eg, Multibandgap)	PV (eg, Multibandgap)	PV (eg, Multibandgap)	PV (on Thin-Film)	TBD
Energy Integration	Separated WPT / SPG	Separated WPT / SPG	Separated WPT / SPG	Integrated WPT / SPG	Integrated WPT / SPG	TBD
Power Management	High-Voltage & Large-Scale PMAD	Superconducting & Large-Scale PMAD	High-Voltage & Large-Scale PMAD	Low-Voltage & Local PMAD	Low-Voltage & Local PMAD	TBD
Insolation	Direct Insolation on PV Arrays	Direct Insolation on PV Arrays	Direct Insolation on PV Arrays	Direct Insolation on PV Arrays	Direct Insolation on PV Arrays	TBD
Architecture	Monolithic / "Stick Built"	Intermediate Modular	Intermediate Modular	Hyper-Modular	Intermediate Modular	TBD
Assy / Construction	In-Space Assembly Platform	Local Construction / Self-Assembly	Local Construction / Assembly	Local Construction / Assembly	Local Construction / Deployable	TBD
"Joints"	Large Rotary @ WP Transmitter	Intermediate Rotary @ PV arrays	Intermediate Rotary @ PV arrays	None	None	TBD
Power Delivery Cycle	~100% (All but Eclipse)	~100% (All but Eclipse)	~100% (All but Eclipse)	~25%	~25-35%	TBD
TBD	TBD	TBD	TBD	TBD	TBD	TBD

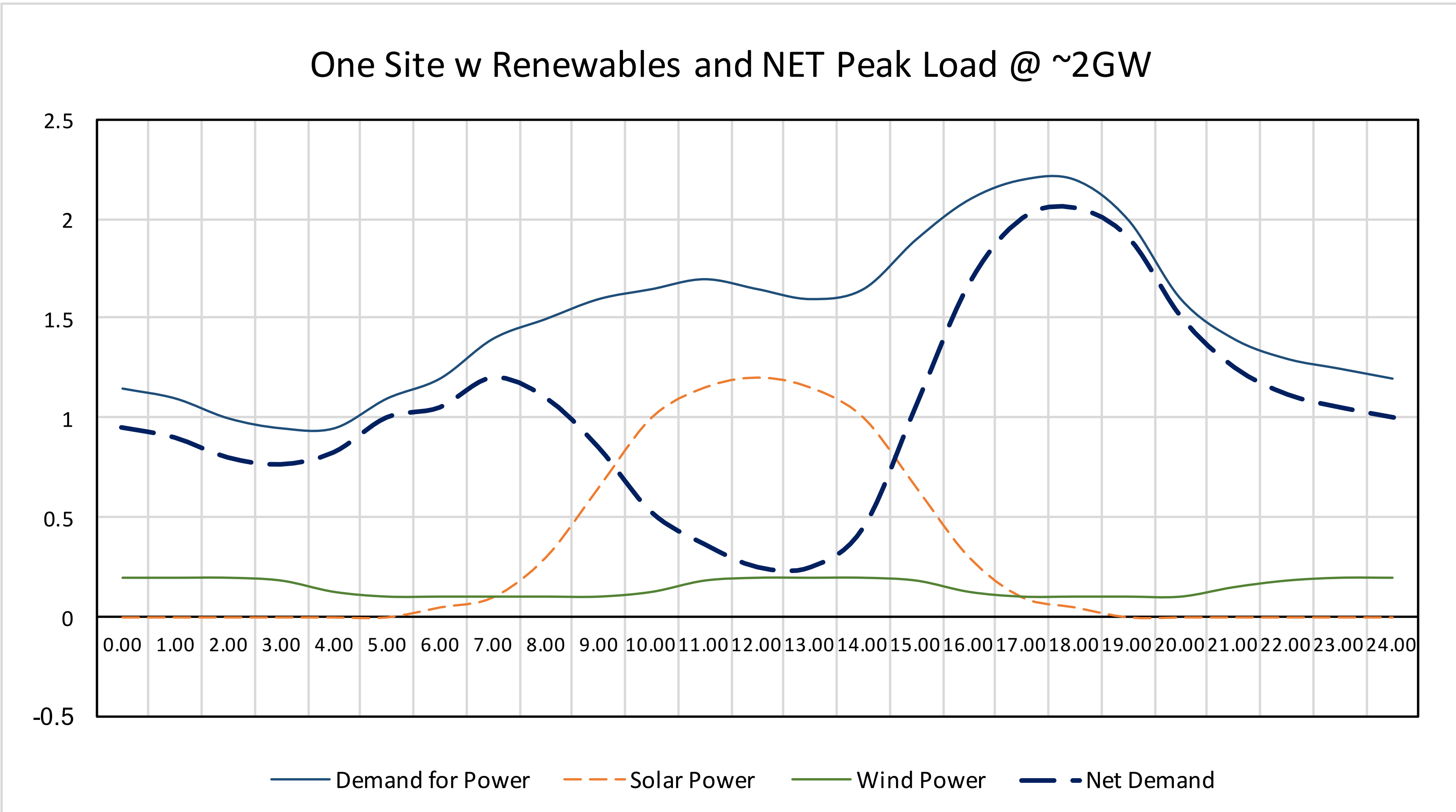
Example Assessment Results

Parameter	ALPHA-Moon (L1 Point)	ALPHA-Earth (GEO)	ALPHA-Earth (MEO)	ALPHA-to-Mars (AMO)	ALPHA-to-Main Belt Asteroid	ALPHA-to - Jovian Moon (e.g., Callisto)
Power Beaming Frequency (GHz)	5.80 GHz	5.80 GHz	5.80 GHz	5.80 GHz	5.80 GHz	5.80 GHz
Solar Flux (W/m²)	1371	1371	1371	590	140	50
Distance from the Sun (km)	149 * 10^6	149 * 10^6	149 * 10^6	227 * 10^6	400 * 10^6	780 * 10^6
WPT Distrance (km)	51,000	35,000	8,000	17,000	8,000	8,000
Transmitter Diameter (m)	2,200	709	340	760	460	460
Receiver Diameter (m)	782	1,564	2,346	1,564	938	938
"OUTPOST" DIAMETER	782	782	782	782	782	782
Concentration factor	4.05	4.54	1.05	12	18.8	52.5
PV input solar flux (W/m²)	5,553	6,224	1,440	7,080	2,632	2,625
PV efficiency	45%	45%	45%	45%	45%	45%
Transmitter efficiency	70%	70%	70%	70%	70%	70%
Space Segment conversion efficiency	31.5%	31.5%	31.5%	31.5%	31.5%	31.5%
Resulting converted SOLAR flux/m² at - PV array	1749	1961	453	2,230	829	827
Beam collection efficiency	23.1%	20.7%	89.9%	18.2%	48.9%	48.9%
Receiver efficiency	87.0%	87.0%	87.0%	87.0%	87.0%	87.0%
Non-Space Segment efficiency	19.9%	17.8%	77.6%	15.7%	42.2%	42.2%
Peak power output desired from Rcvr (MW)	350	350	350	350	350	350
Required collected SUNLIGHT (MW)	*5,574*	*6,226*	*1,432*	*7,060*	*2,631*	*2,631*
Required PV area for collection (km²)	1.00	1.00	0.99	1.00	1.00	1.00
Required diameter for solar collection (m)	1,131	1,129	1,125	1,128	1,128	1,130
Transmitted power (MW)	1,756	1,961	451	2,224	829	829
Transmitter power density (kW/m²)	0.46	4.97	4.97	4.90	4.99	4.99
Ground Receiver Power density (W/m²)	952.5	234.6	237.5	231.2	798.9	798.9
Transmitter Mass (@ ~3 kg / m^2) - in MT	11,398	1,184	272	1,360	498	498
PV Mass (@ ~1 kg / m^2) - in MT	791	785	777	785	785	789
Reflector Array Mass (@ 1 kg / m^2) in MT	3,204	3,565	816	9,415	14,751	41,412
TOTAL SPS MASS (non-Rectenna) in MT	15,393	5,535	1,865	11,560	16,033	42,699
TOTAL MASS "from Earth" (non-Rectenna) in MT	12,189	1,969	1,049	2,145	1,283	1,287

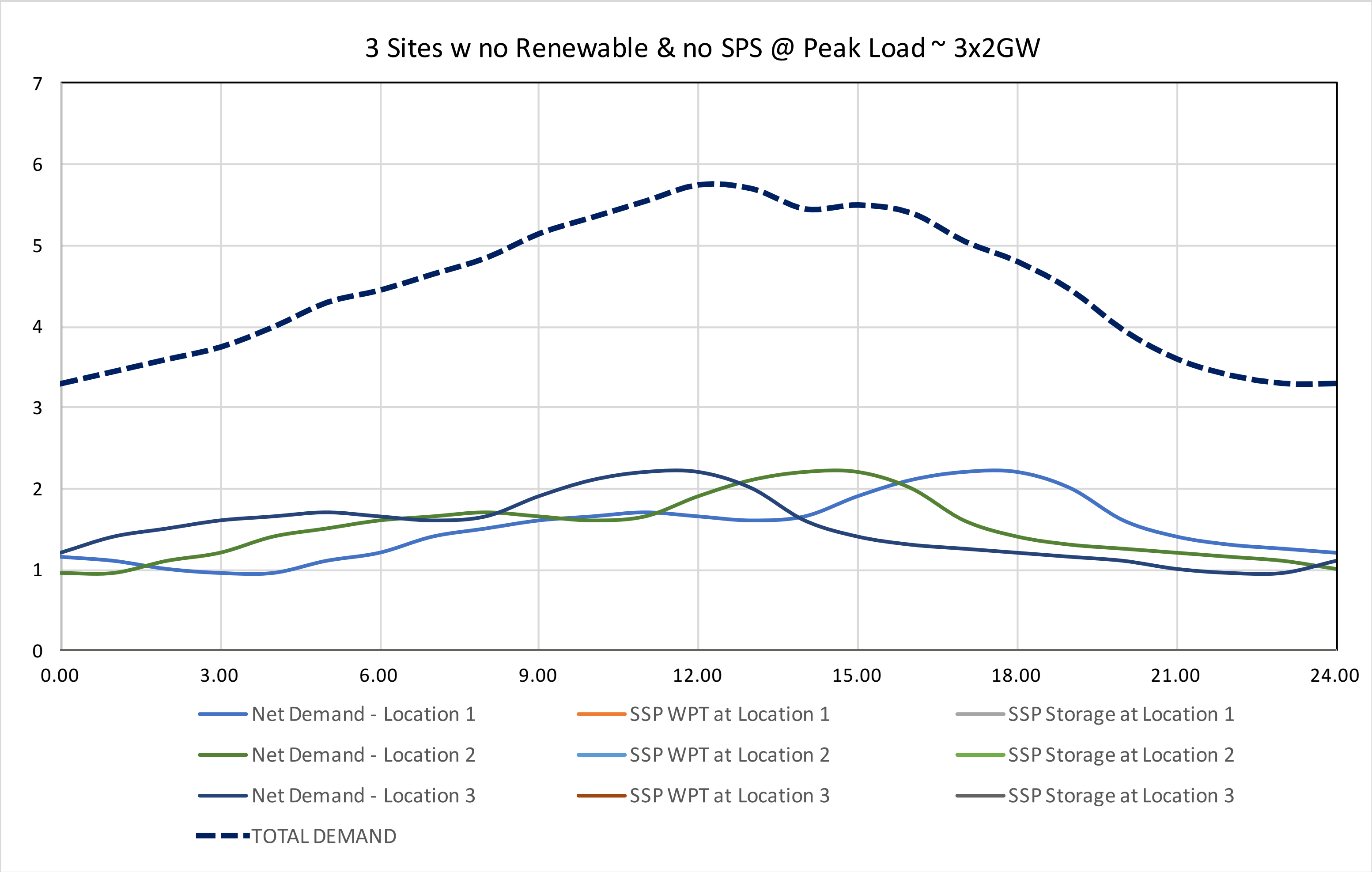
Another Topic: Integration with Ground Solar



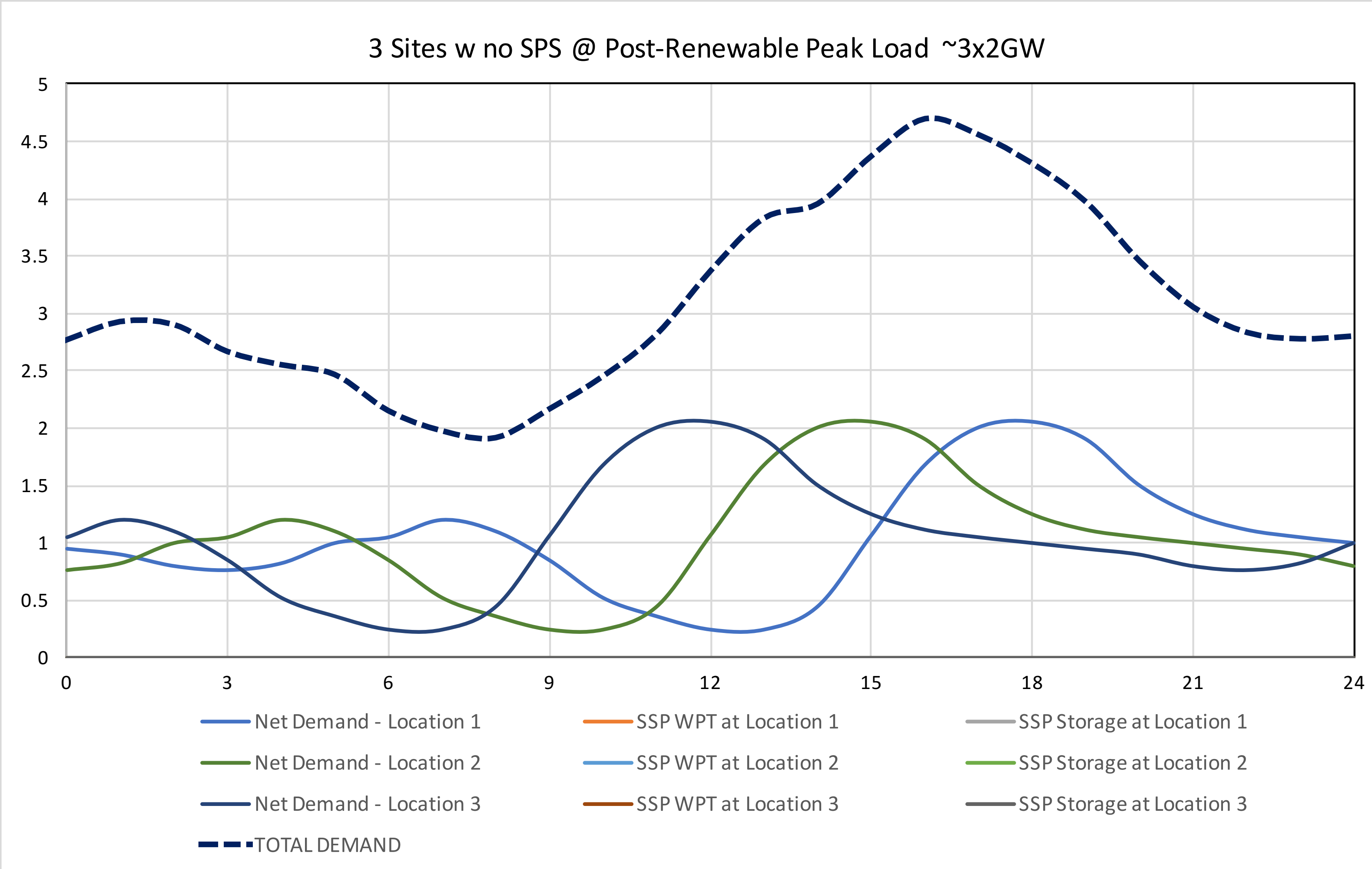
Another Topic: Integration with Ground Solar (2)



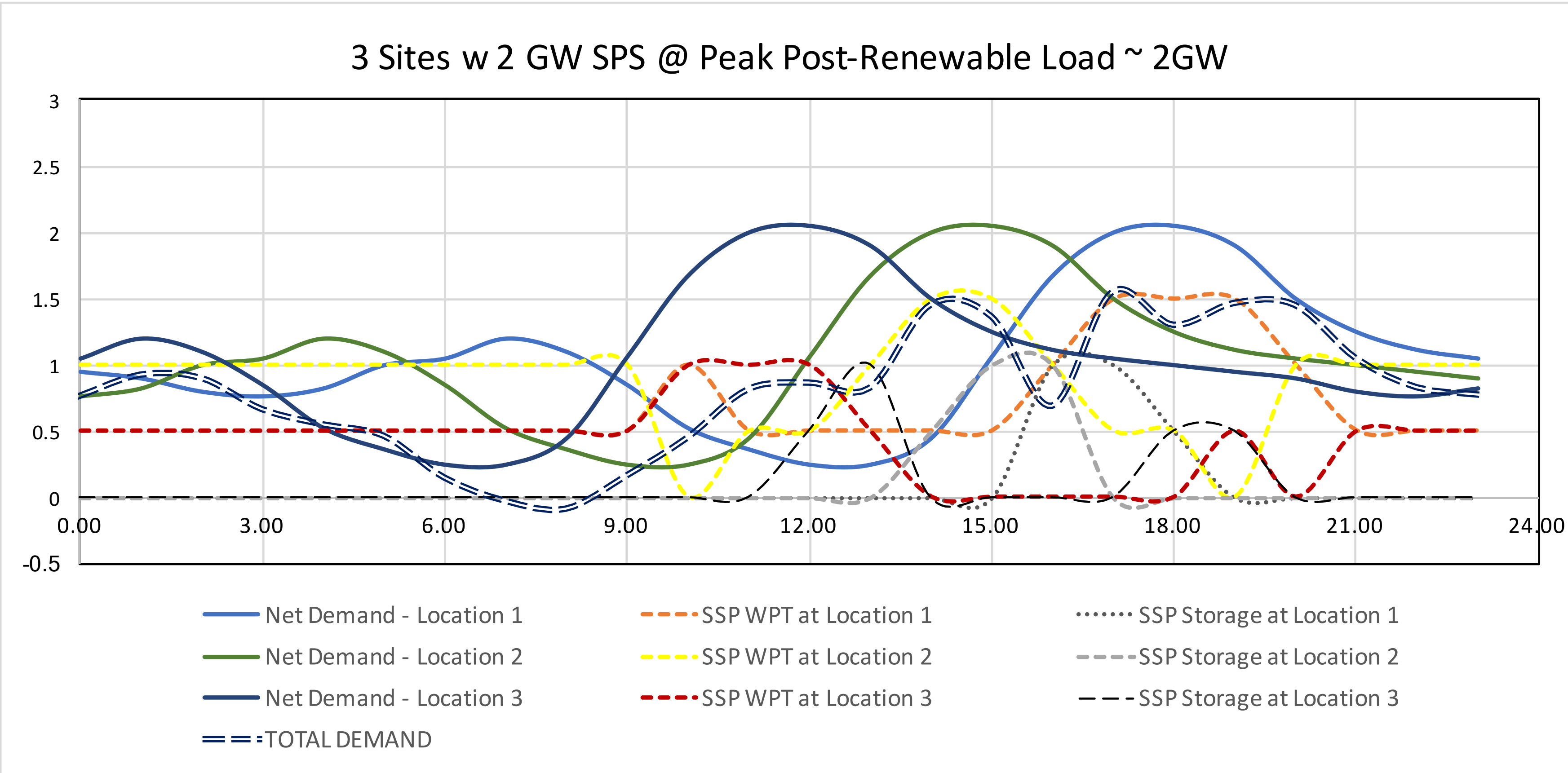
Another Topic: Integration with Ground Solar (3)



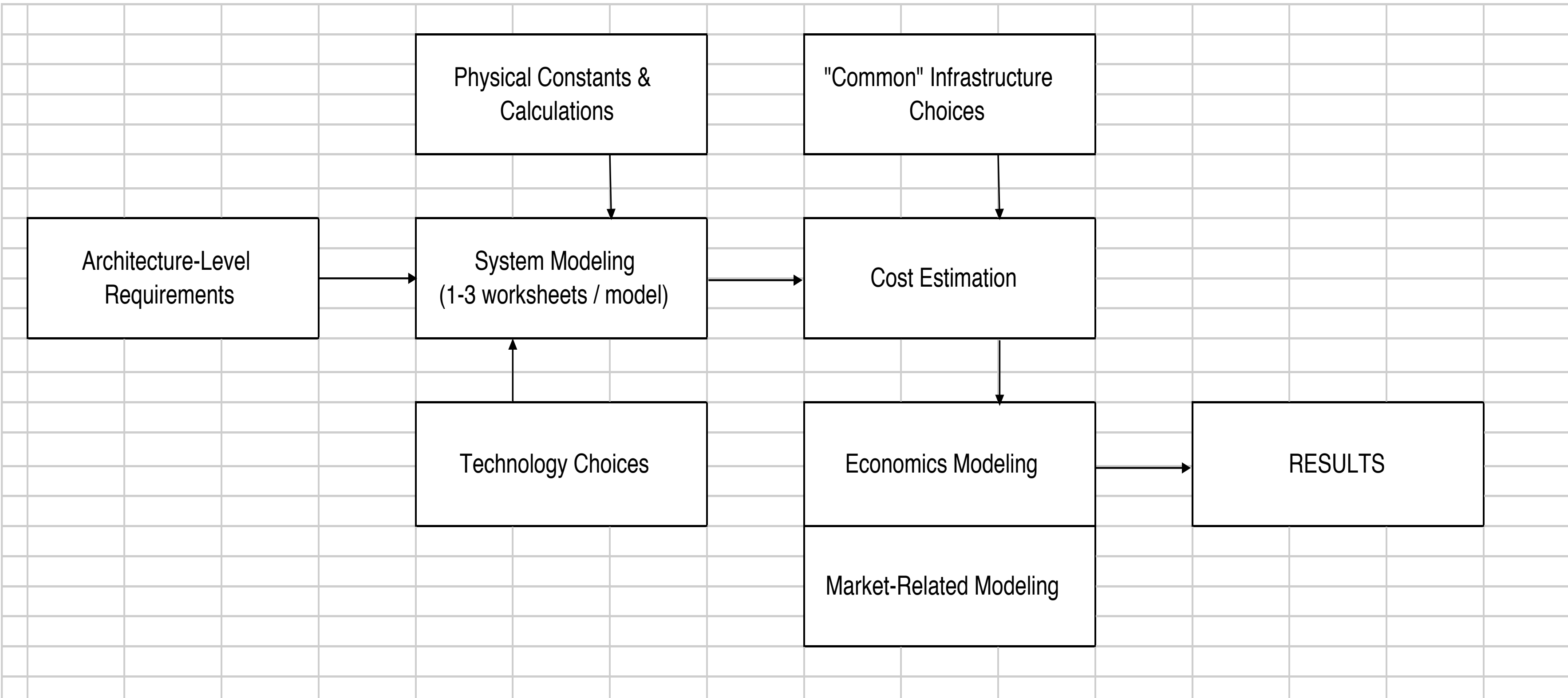
Another Topic: Integration with Ground Solar (5)



Another Topic: Integration with Ground Solar (6)



Assessment Approach



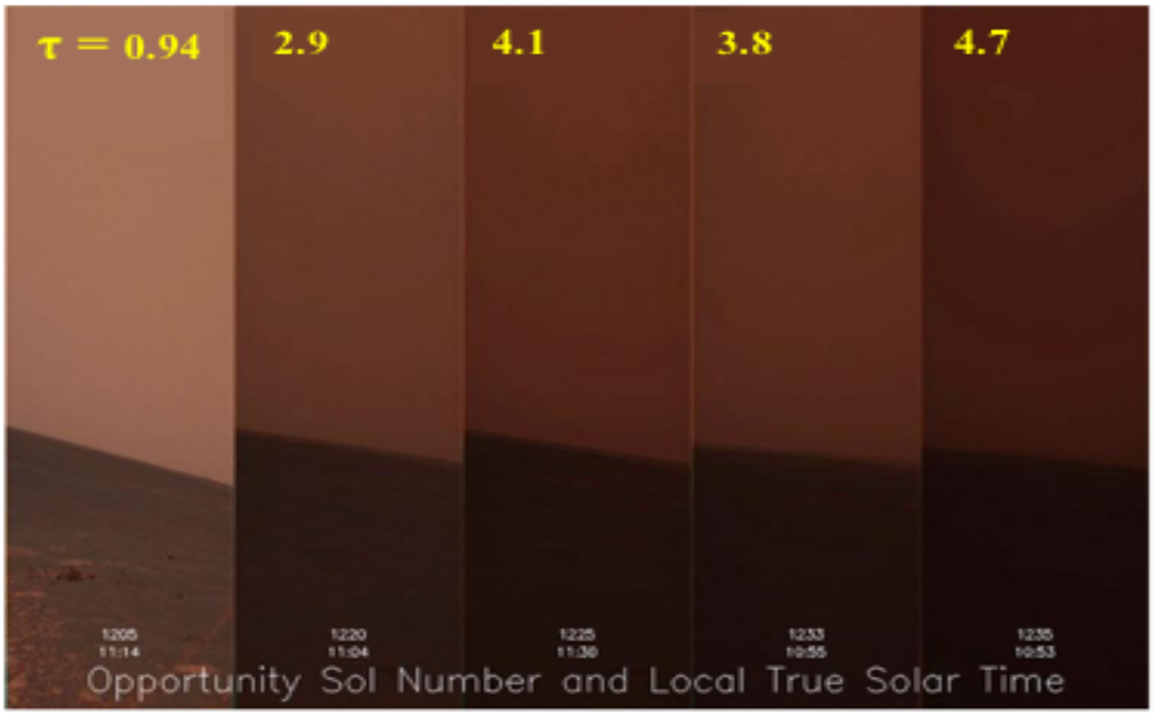
CLOSING

SG 3.31 Execution

- **March 2018 – Begin Study**
- May 2018 – Kick-off Workshop at SPS-2018
- September 2018 – Working Meeting (IAC 2018 / Bremen); present interim results at IAC C3.1 Session
- March 2019 – Working Meeting (IPC)
- **June 2019 – Workshop at ISDC 2019 – *THIS MEETING***
- Summer 2019 – Working at ISTS 2019 - *Planned*
- Fall 2019 – Working Meeting at IAC 2019 (Washington, DC)); present interim results at IAC C3.1 Session
- March 2020 – Working Meeting (IPC)
- May 2020 – Workshop at ISDC 2020
- Fall 2020 – Working Meeting (IAC 2020 / Dubai)); present interim results at IAC C3.1 Session
- **March 2021 - Complete study**

Back-up Slides

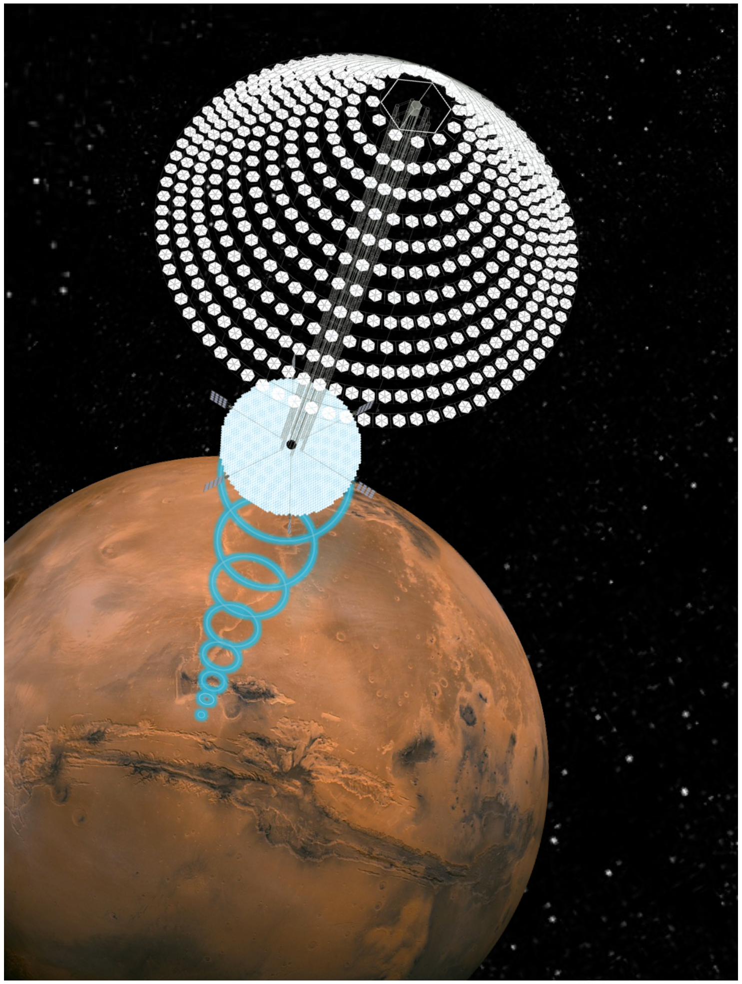
Mars: What about Surface Solar?



- For small to intermediate scale, fixed locations nuclear power is promising (e.g., 1 kW RTG-type, 10-100 kW SP-100 type)
- Surface solar has been used for small rovers
- However, solar on the surface will be highly variable and vulnerable to being covered by dust / storms

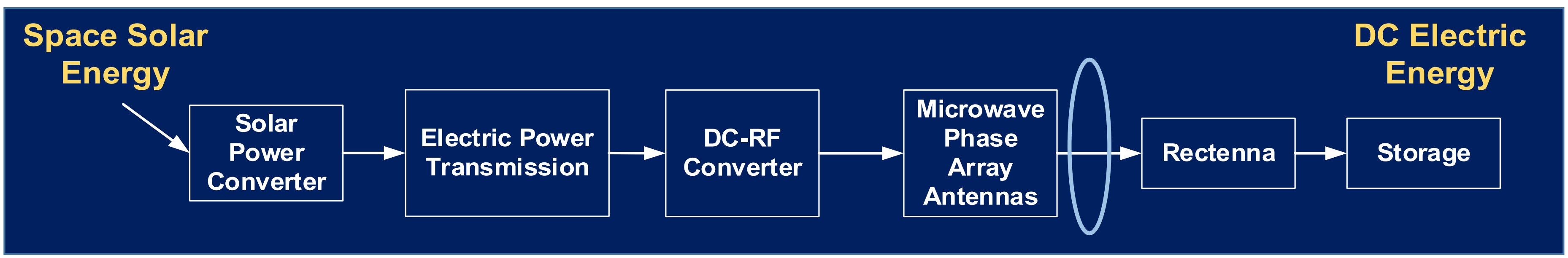
Space Solar @ Mars

- For larger-scale and longer term Mars surface activities (>1 MW or in multiple locations), significant, reliable and “dispatchable” power may be required
- Solar placed in Mars orbit can wirelessly transmit provide regular, reliable power to locations globally
- Example Concept: highly modular SPS, based in a near-polar Mars orbit
  - Power delivered ~3-6 times per day (depending on Latitude)
  - Stored on surface (up to 12 hours?)
  - Globally available power (with deployment / redeployment of local receivers)



Example: Mars SSP System Architecture

- Power satellite is located in Mars polar orbit guesstimate: ~500 km
- Insolation at Mars: 589W/m^2
- Rare / short eclipse: < 1 hr shadowing occasionally
- Use microwave to mmwave to transmit power.
- Goal: power density @ 1,000 W/m^2 for 10 minutes x 3-6 times / day (average: 20-50 W/m^2)
- Wide range of possible power levels delivered – continuous with storage – anywhere on the surface



WPT Attenuation:
Free space, gaseous, dust