A Path Forward for Space Solar Power

SPS-ALPHA Demonstrations to Operations

John C. Mankins
Founder and President

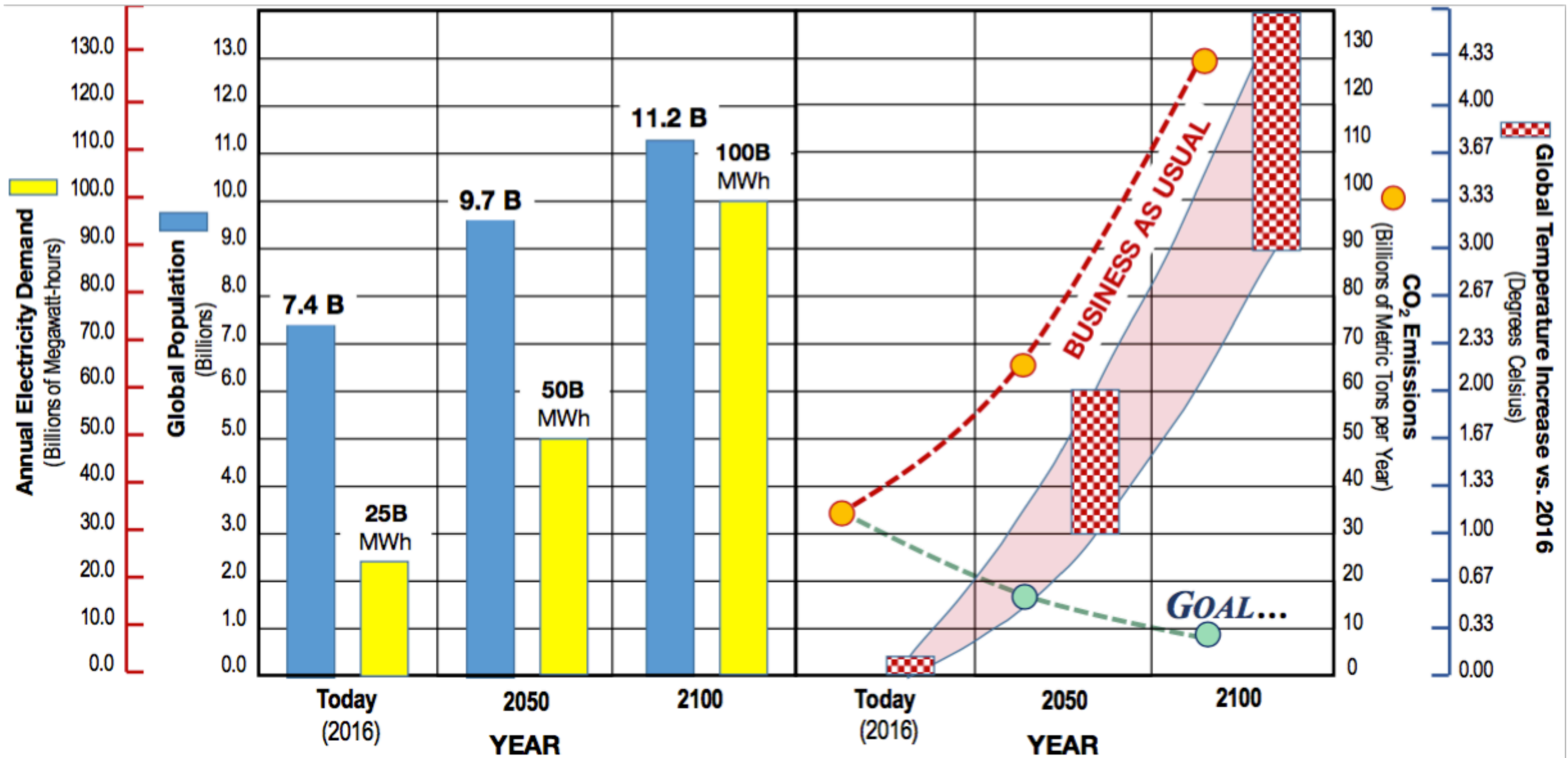
MANKINS
SPACE TECHNOLOGY

24-28 May 2017

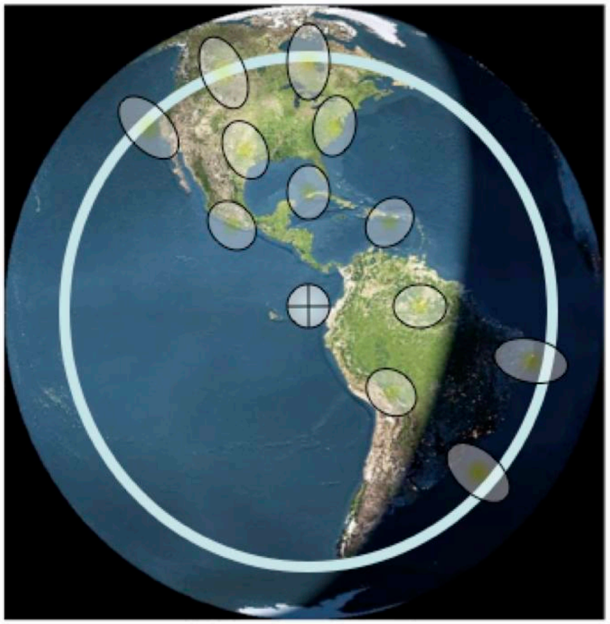
International Space Development Conference (ISDC 2017)

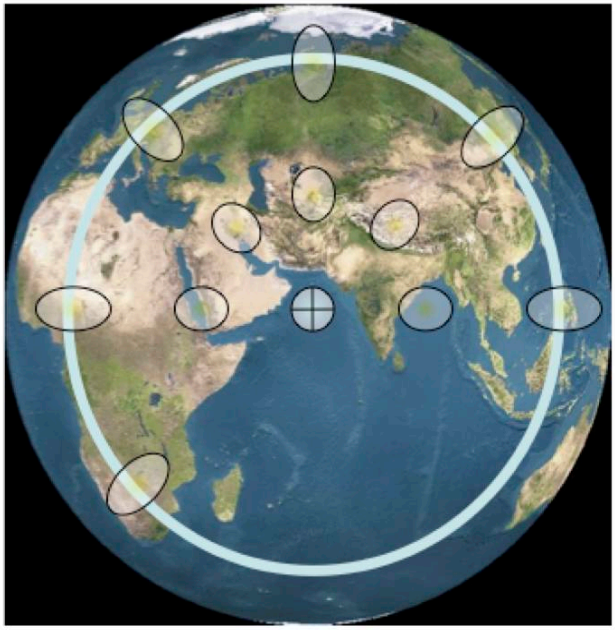
St. Louis , Missouri USA

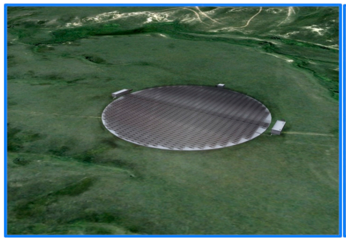
Why do we Need New & Sustainable Energy Sources…?

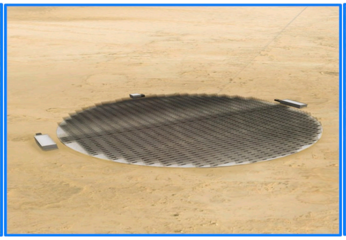


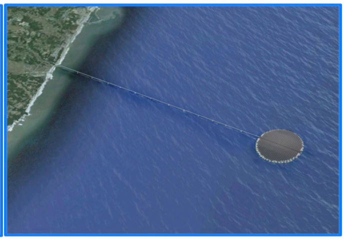
The Vision of Space Solar Power
Affordable / Dispatchable Solar Energy 365-24-7











SPS-ALPHA Mk-II Overview

Incident Sun Light in GeoStationary Earth Orbit @ 1358 W/m^2

↓

Photovoltaic (PV) Conversion @ 35-50% Efficiency and ~1000 W/kg

↓

Phased Array Conversion to Microwave RF Beam @ 2.45 GHz or 5.8 GHz and >70% Efficiency Goal

↓

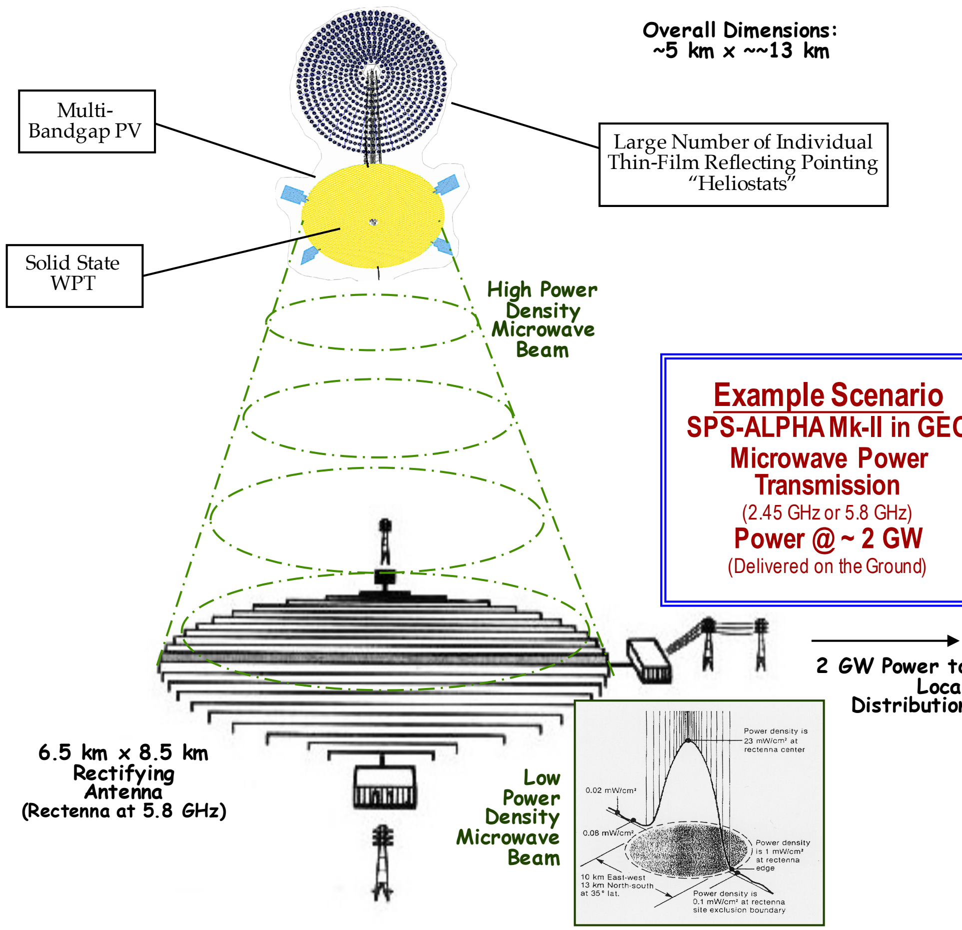
Wireless Power Transmission from Space to Earth @ ~95% Efficiency Goal

↓

Rectifying Antenna Conversion of RF to Voltage @ >85% Efficiency Goal

↓

Management & Distribution of Baseload Power to Local Grid (e.g., 1.2-4.8 GW, 1-10 Beams)



Example Scenario

SPS-ALPHA Mk-II in GEO

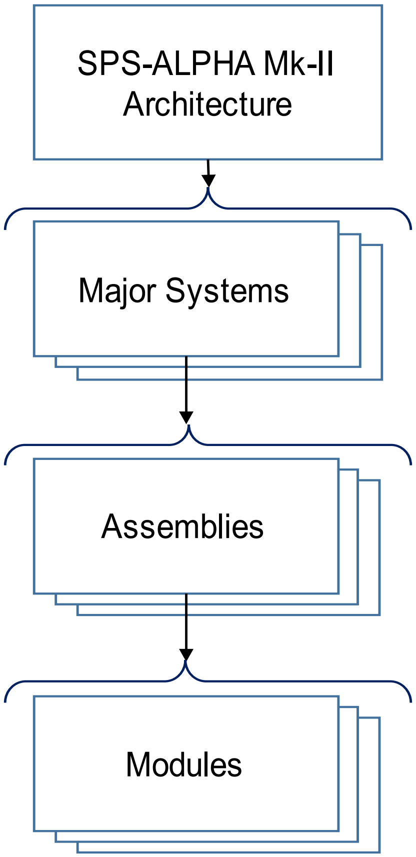
Microwave Power Transmission

(2.45 GHz or 5.8 GHz)

Power @ ~ 2 GW

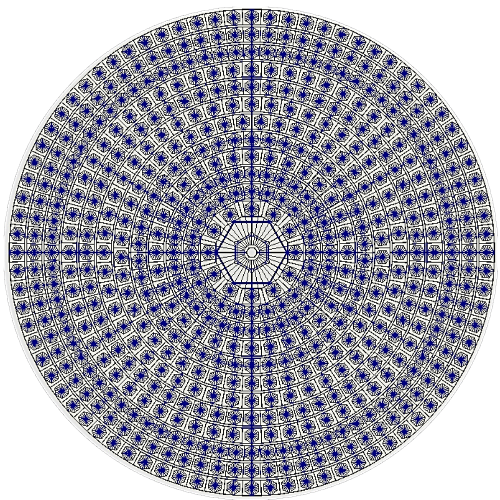
(Delivered on the Ground)

SPS-ALPHA Mk-II Overview
Architectural Approach



- At the highest Level, the full Architecture, comprising the SPS Platform, Ground Systems, Supporting Infrastructure, etc.
- At the 2nd Level, the Major Systems within the Architecture
  - Within the Platform, comprising the Reflector Array, etc.
  - On the Ground, including the Rectenna, etc.
  - In the Transportation Infrastructure, including the Launch Vehicle, etc.
- At the 3rd Level, the Assemblies within each Major System
  - Including the Reflector Array Assemblies, comprising interconnects of two types, truss structures, reflector deployment modules, etc.
- At the 4th Level, the various modules that comprise the SPS-ALPHA Mark-II Architecture

SPS-ALPHA Mk-II Overview Concept Details



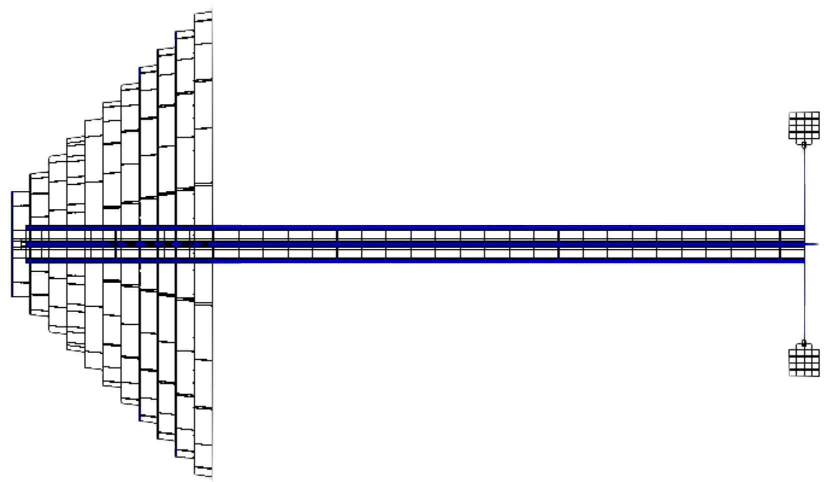
TOP VIEW

Max Diameter < 6 km

"Stepped Cylinders" Conical Structural System

Array of Several 1000s of Thin-Film Heliostats (Each @ ~1900 m^2)

Oversized Sail Array to use Light Pressure for Station-Keeping (Partial)



SIDE VIEW

Total Length ~ 13 km

Reflectors / Reflector Array / Backbone sized to Provide Specific Concentration (~3:1) Uniformity of Illumination (<3%)

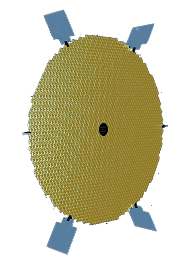
Gravity Gradient Stabilized (With Artificial Gravity at ISAAC Facility at "Top" of Structural Backbone)

Truss-Structure Connecting Heliostat Array and PV-WPT Array

Docking / Construction / Servicing Station at Far-End from PV-WPT Array

"Trim" Sails use Light Pressure for Station-Keeping (Partial)

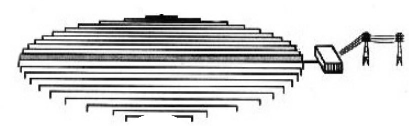
LEO-GEO SEP OTVs "Double" as On-Board Propulsion (Post Assembly)



BOTTOM PERSPECTIVE

Diameter ~ 1.7 km

Hyper-modular PV+WPT Array)



GROUND RECEIVER

Diameter ~ 6 km

Local Modular Energy Storage (up to ~2.5 GWh)

SPS-ALPHA Mk-II Overview Architecture Elements

1. SPS-ALPHA Mark-II Platform Systems (M.1)	2.0 Ground Receiver Systems (M.2)

• Inter-connect Modules M.1.1)
  • Inter-connect - Type 1 (M.1.1.1)
  • Inter-connect - Type 2 (M.1.1.2)
• SPS Bus Module (M.1.2)
• SPS Frame Modules M.1.3)
  • Frame - Type 1 (Long; M.1.3.1)
  • Frame - Type 2 (Short; M.1.3.2)
• Wireless Power Transmitter Module (M.1.4)
• Solar Power Generation Module (M.1.5)
• Thin-Film Heliostat: Reflector & Deployer Module (M.1.6)
• Robotic Arm Manipulator System Module (M.1.7)
• Propulsion Module (M.1.8)
• WiFi Router Module (M.1.9)
• External Communications Module (M.1.10)
• Autonomous Rendezvous & Docking (AR&D) System Module (M.1.11)
• "Kernel" Core Module (M.1.12)
	• M.2.1 Rectenna Antenna (M.2.1)
	• Pilot Signal Transmitter (M.2.2)
	• Range Safety & Control (M.2.3)
	• Energy Storage Systems (M.2.4)
	• Grid Interfaces (M.2.5)
	3.0 Launch Systems (M.3)
	• Launch Vehicle (M.3.1)
	• Payload Support & Packaging (M.3.2)
	• Transportation Ground Infrastructure (M.3.3)
	• Transportation Mission Control & Communications (M.3.4)
	4.0 In-Space Transportation Systems (M.4)
	• Orbital Transfer Power Systems (M.4.1)
	• Orbital Transfer Thermal Systems (M.4.2)
	• Orbital Transfer Ground Infrastructure (M.4.3)
	5.0 SPS Mission Control Center (M.5)

SPS-ALPHA Mk-II Overview
Architecture Elements / Space Segments

1.0 Power Conversion Array Assembly (A.1)

- Inter-connect Modules M.1.1)
    - Inter-connect - Type 1 (M.1.1.1)
    - Inter-connect - Type 2 (M.1.1.2)
- SPS Bus Module (M.1.2)
- Wireless Power Transmitter Module (M.1.4)
- Solar Power Generation Module (M.1.5)
- WiFi Router Module (M.1.9)
- External Communications Module (M.1.10)

2.0 Primary Reflector Array Assembly (A.2)

- Inter-connect Modules M.1.1)
    - Inter-connect - Type 1 (M.1.1.1)
    - Inter-connect - Type 2 (M.1.1.2)
- SPS Bus Module (M.1.2)
- SPS Frame Module M.1.3)
    - Frame - Type 1 (Long; M.1.3.1)
    - Frame - Type 2 (Short; M.1.3.2)
- Thin-Film Heliostat: Reflector & Deployer Module (M.1.6)

3.0 Platform Backbone Structure Assy (A.3)

- Inter-connect Modules M.1.1)
    - Inter-connect - Type 1 (M.1.1.1)
    - Inter-connect - Type 2 (M.1.1.2)
- SPS Bus Module (M.1.2)
- SPS Frame Module M.1.3)
    - Frame - Type 1 (Long; M.1.3.1)
    - Frame - Type 2 (Short; M.1.3.2)

4.0 SPS Orbital Operations Assembly (A.4)

- Inter-connect Modules M.1.1)
    - Inter-connect - Type 1 (M.1.1.1)
- SPS Bus Module (M.1.2)
- Solar Power Generation Module (M.1.5)
- Propulsion Module (M.1.8)
- WiFi Router Module (M.1.9)
- External Communications Module (M.1.10)
- Autonomous Rendezvous & Docking (AR&D) System Module (M.1.11)

5.0 SPS On-Board Operations Assy (5.6)

- Inter-connect Modules M.1.1)
    - Inter-connect - Type 1 (M.1.1.1)
    - Inter-connect - Type 2 (M.1.1.2)
- SPS Bus Module (M.1.2)
- SPS Frame Module M.1.3)
    - Frame - Type 1 (Long; M.1.3.1)
    - Frame - Type 2 (Short; M.1.3.2)
- Solar Power Generation Module (M.1.5)
- Robotic Arm Manipulator System Module (M.1.7)
- WiFi Router Module (M.1.9)
- Orbital Transfer Ground Infrastructure (M.4.3)

6.0 SPS Kernel Assembly (A.6)

- "Kernel" Core Module (M.1.12)
- Autonomous Rendezvous & Docking (AR&D) System Module (M.1.11)
- Orbital Transfer Ground Infrastructure (M.4.3)

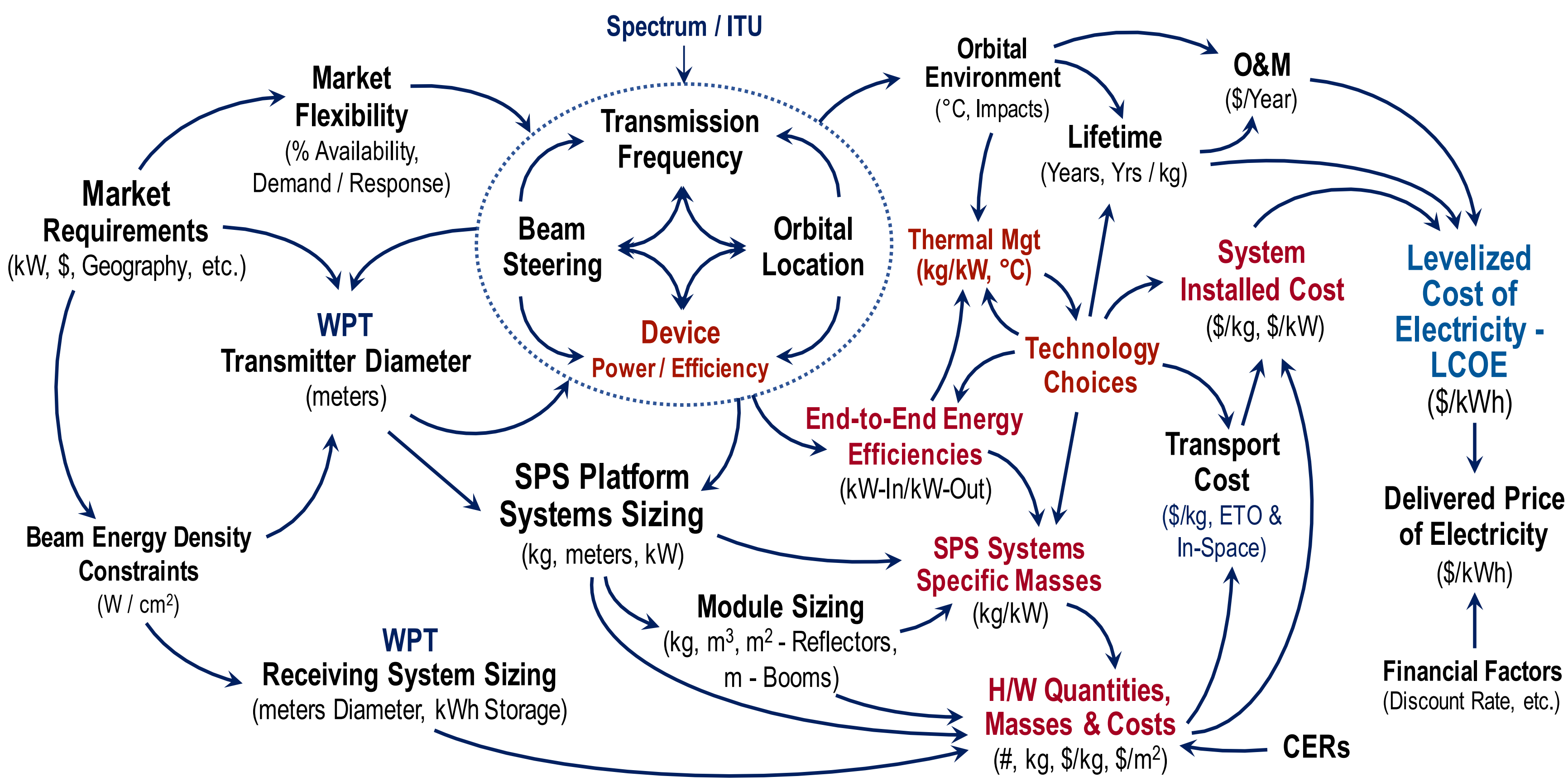
SPS-ALPHA Mk-II Overview
Summary Characteristics

LCOE	$0.0289	$ / kW-hr	Installed Cost	$11.4483	Billion, $	Economic Lifetime	30	years
COST/Watt	$5.50	$ per Watt	SPS Platform Mass	9,192	MT	Total Energy	547,322	GW-hrs
Power Delivered	2,081.23	MW	SPS Cost per kg	$289		Energy to Deploy	365,524,963	kW-hours

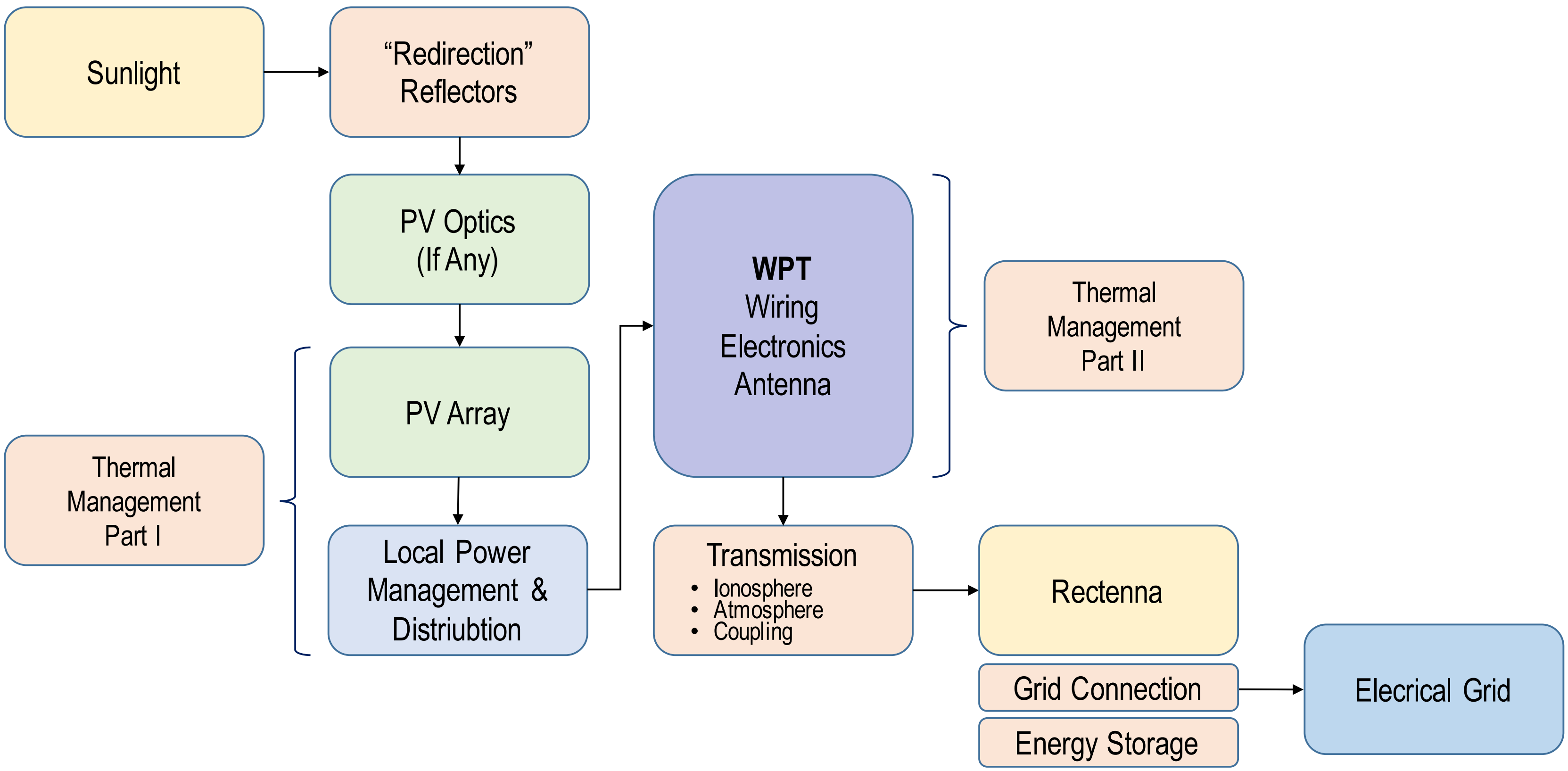
- Typical analysis results…
  - ✓ Power delivered > 2 GW
  - ✓ Mass in GEO at ~ 9200 MT @ ~$11.4B
  - ✓ Cost of Electricity ~3 ¢ kWh, with ETO @ $600 / kg
  - ✓ Economic Lifetime @ 30 years (assumed)
  - ✓ With various "moderate" advancement assumptions for key performance parameters / technologies

Sunlight @ 1 AU	1,358	Watts/m^2
Reflector - Tailored Efficiency	90.0%	Percent
PV Efficiency	45.0%	Percent
WPT Transmitter Efficiency	70.0%	Percent
Atmospheric Absorption	1.0%	Percent
Receiver "Interception" of Beam	96.0%	Percent
WPT Receiver Effiency	87.0%	Percent

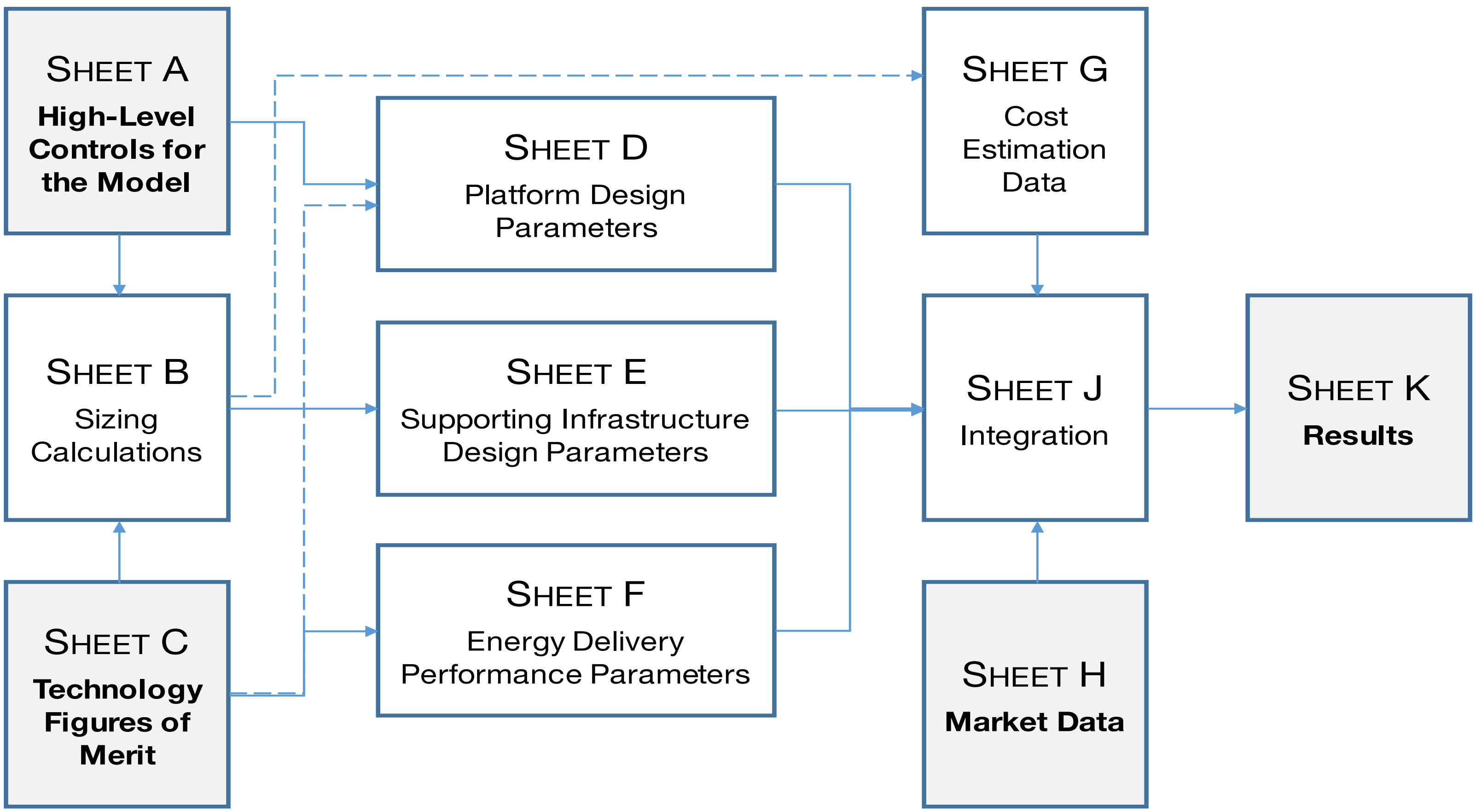
Modeling SPS-ALPHA Mark-II Interrelationships Among KPPs



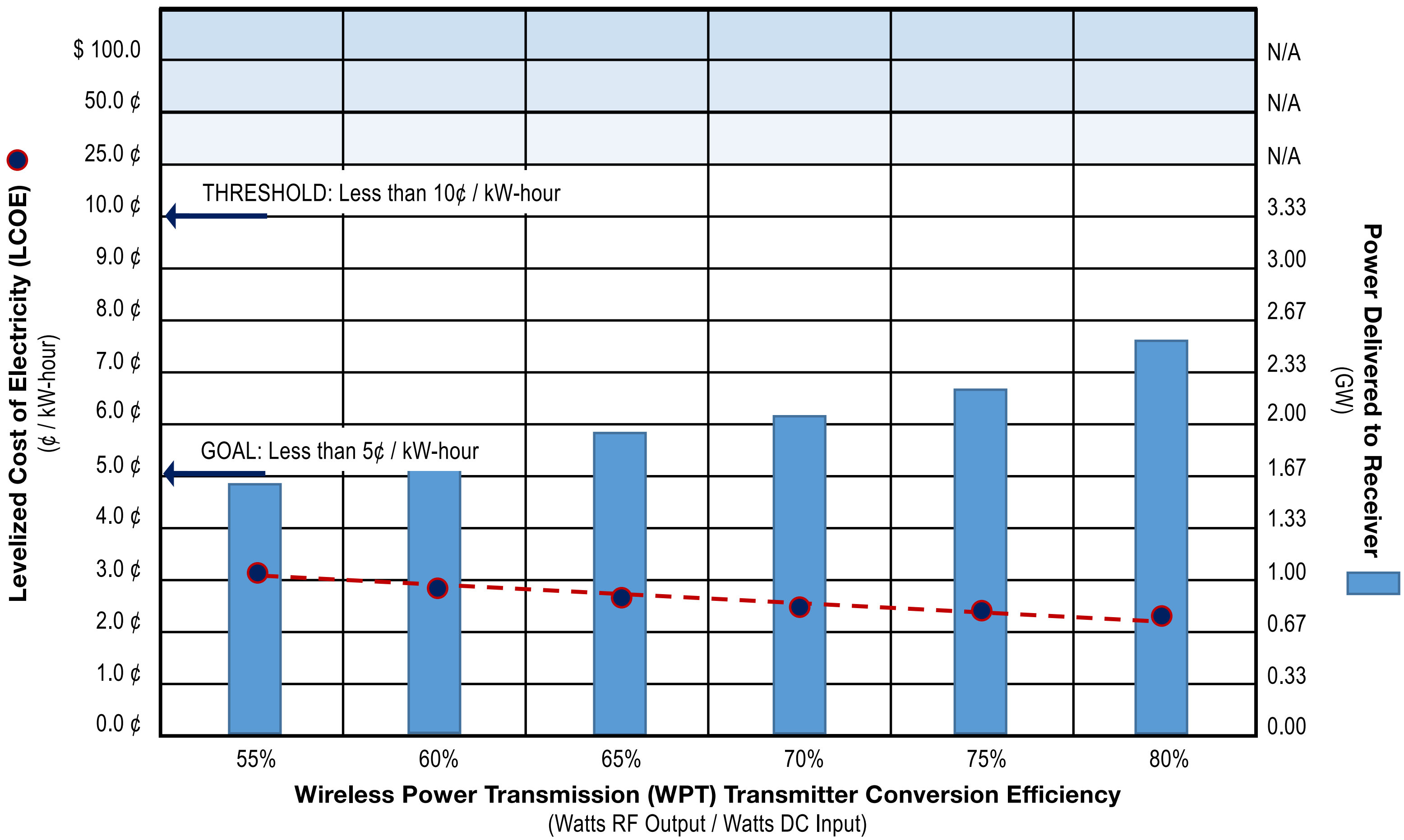
Modeling SPS-ALPHA Mark-II End-to-End Energy Analysis



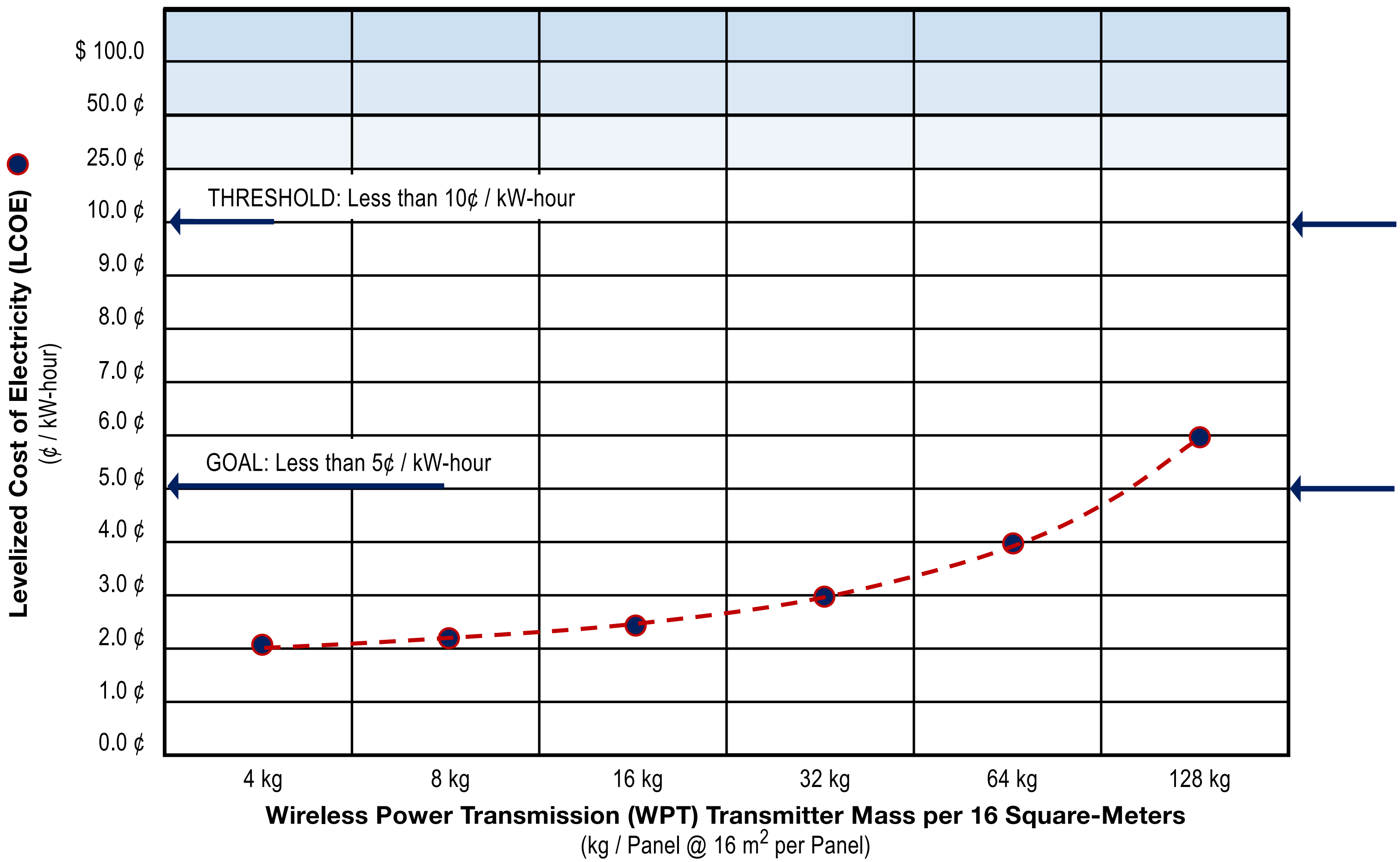
SPS-ALPHA Mark-II Modeling
Excel-Based Modeling Approach (Overview)



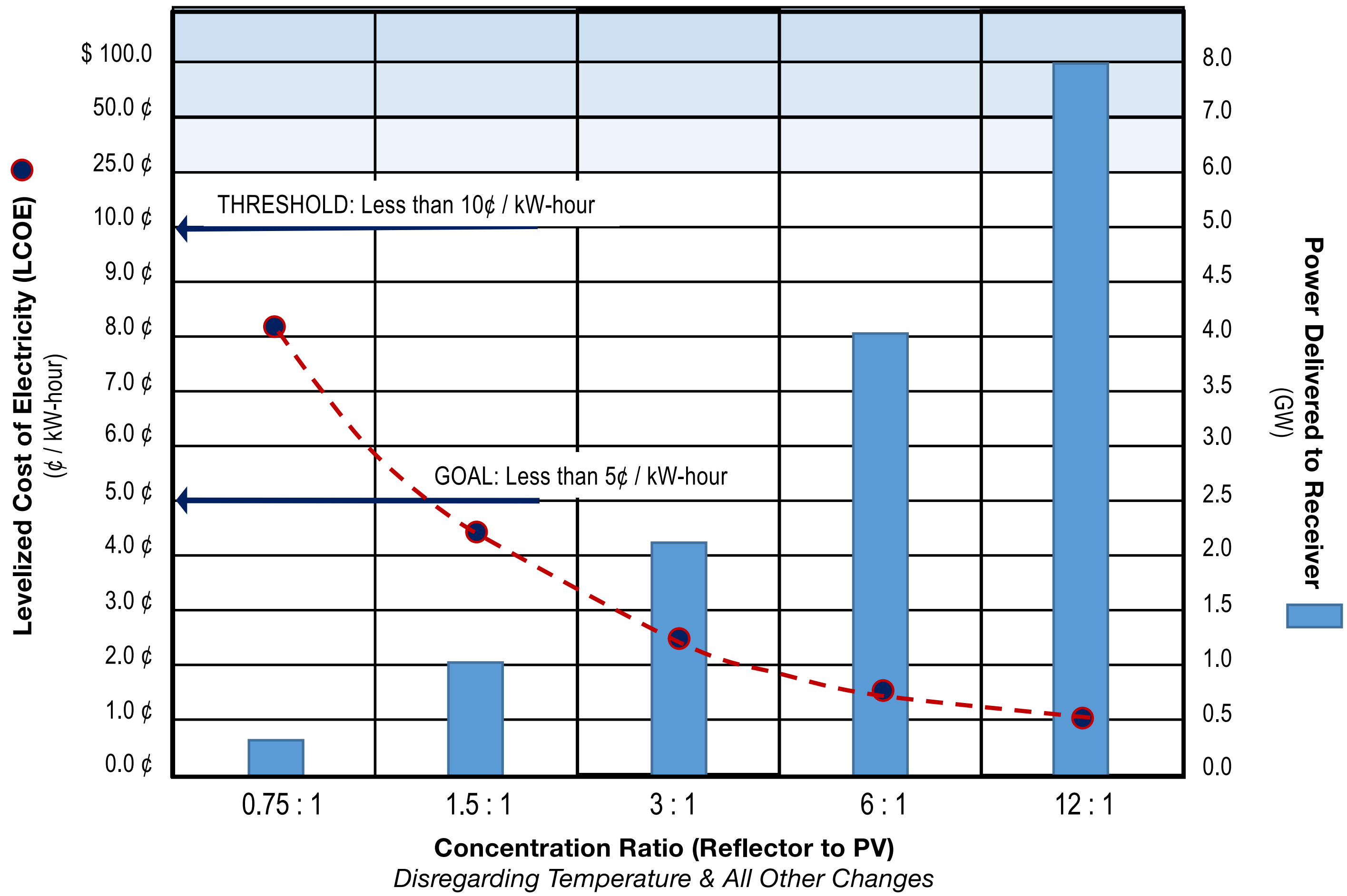
SPS-ALPHA Mark-II Modeling Results
System Results as a Function of WPT Efficiency



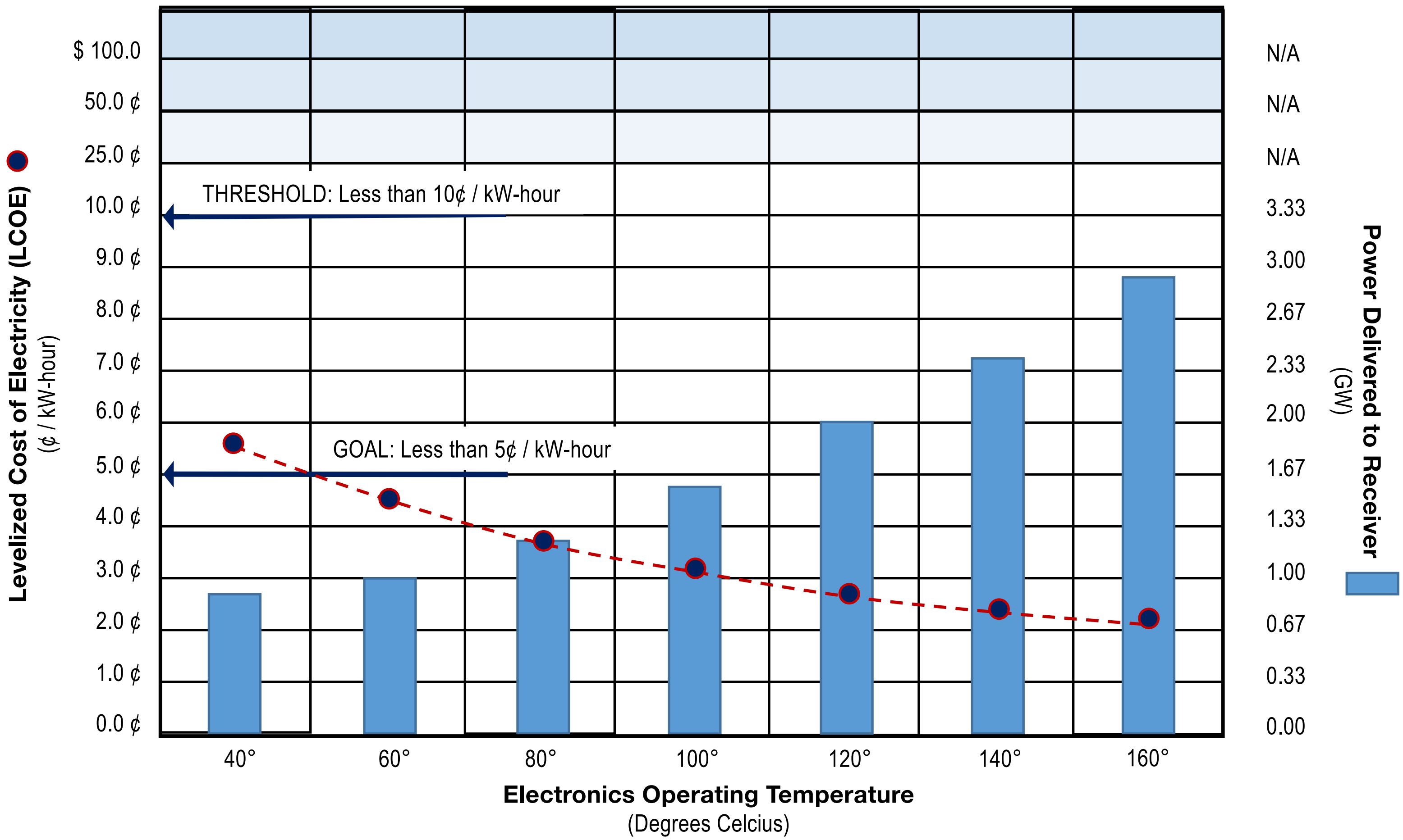
SPS-ALPHA Mark-II Modeling Results
System Results as a Function of WPT Areal Mass



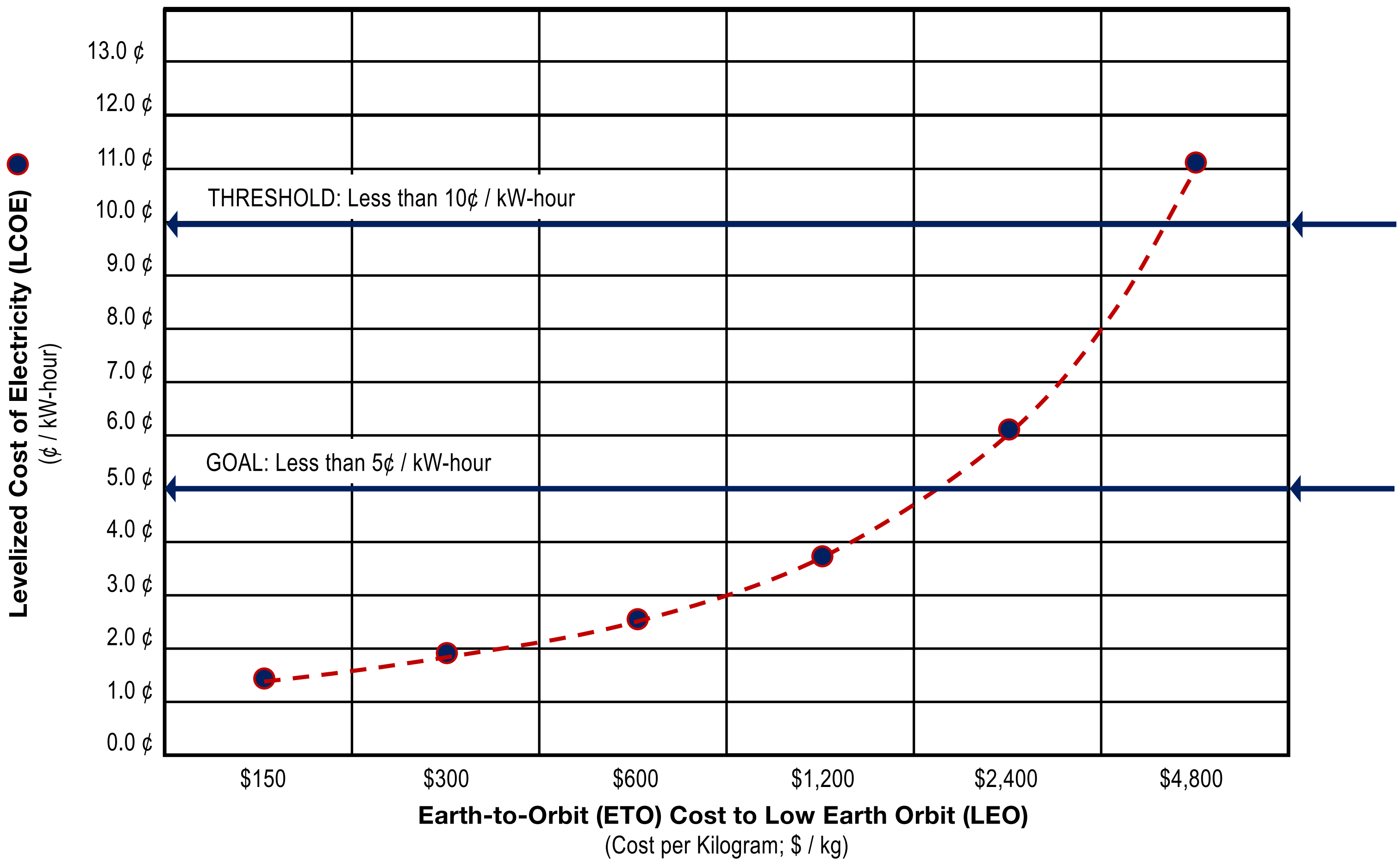
SPS-ALPHA Mark-II Modeling Results
System Results vs. Concentration Ratio



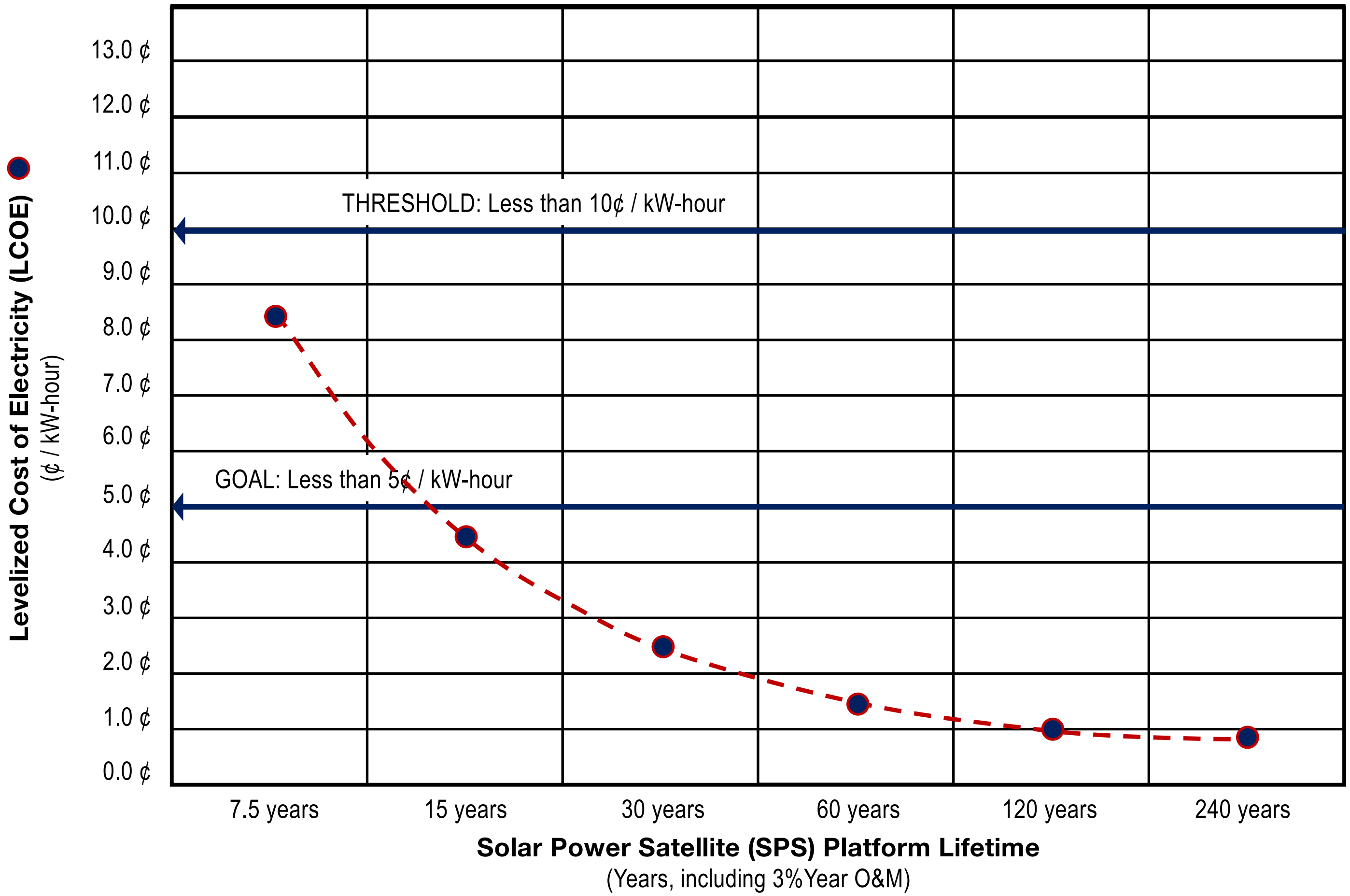
SPS-ALPHA Mark-II Modeling Results
System Results vs. Operating Temperature



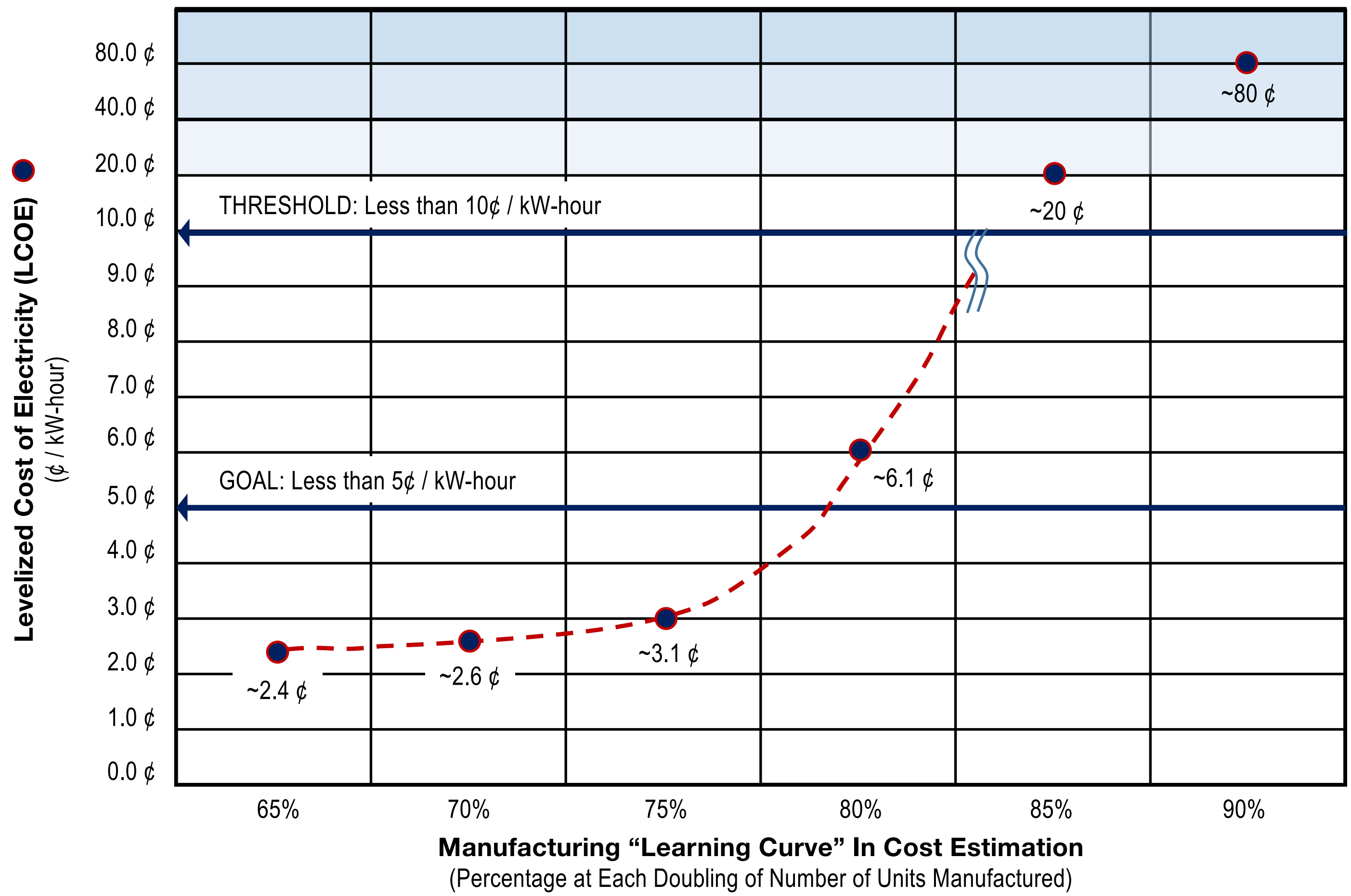
SPS-ALPHA Mark-II Modeling Results
System Results vs. ETO Costs



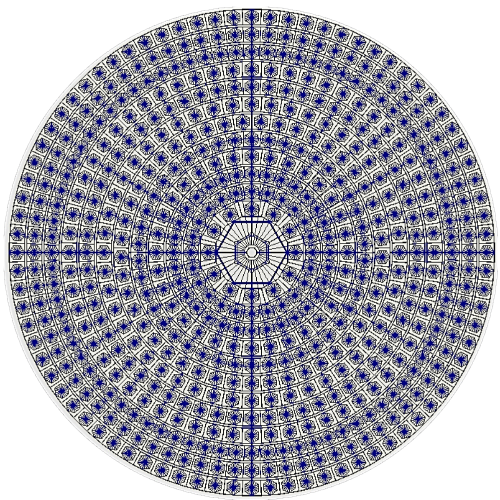
SPS-ALPHA Mark-II Modeling Results
System Results vs. Platform Lifetime



SPS-ALPHA Mark-II Modeling Results
System Results vs. Platform Mfg. Learning Curve



SPS-ALPHA Mk-II Overview
Concept Details – Baseline @ Full-Scale



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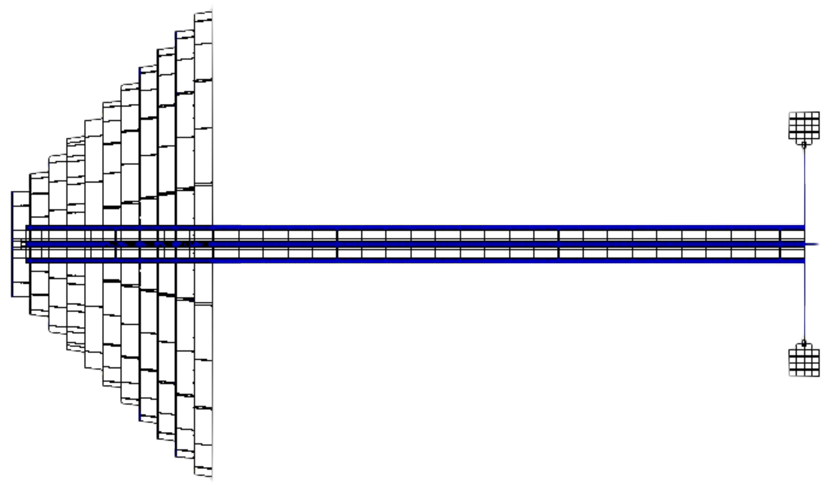

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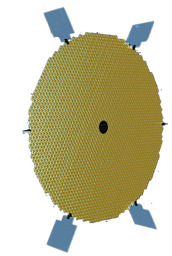
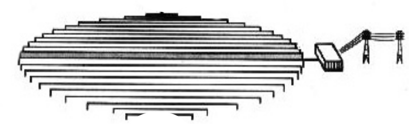


BOTTOM PERSPECTIVE

Diameter ~ 1.7 km

Hyper-modular PV+WPT Array)



GROUND RECEIVER

Diameter ~ 6 km

Local Modular Energy Storage (up to ~2.5 GWh)

SPS-ALPHA Design Reference Missions

DRM 1	Installed Cost	"Platform Margin"	Reserve / Revenue
SPS Demo @ 20 kW in LEO	@ $116 M	100 %	$43 M
DRM 1a	Installed Cost	"Platform Margin"	Reserve / Revenue
10 x Commsats @ 20 kW in GEO	@ $130 M	400 %	$79 M
DRM 2	Installed Cost	"Platform Margin"	Reserve / Revenue
1 x MegaSat @ 100 kW in GEO	@ $289 M	275 %	$169 M
DRM 2a	Installed Cost	"Platform Margin"	Reserve / Revenue
10 x MegaSat @ 100 kW in GEO	@ $153 M	275 %	$69 M
DRM 3	Installed Cost	"Platform Margin"	Reserve / Revenue
1 x FOB Power @ 20 MW fm GEO	@ $2.98 B	100 %	$614 M
DRM 3a	Installed Cost	"Platform Margin"	Reserve / Revenue
10 x FOB Power @ 20 MW fm GEO	@ $2.39 B	100 %	$316 M
DRM 4	Installed Cost	"Platform Margin"	Reserve / Revenue
1 x Niche Power @ 250 MW fm GEO	@ $7.05 B	100 %	$1,387 M
DRM 4a	Installed Cost	"Platform Margin"	Reserve / Revenue
20 x Niche @ 250 MW fm GEO	@ $5.06 B	100 %	$391 M
DRM 5	Installed Cost	"Platform Margin"	Reserve / Revenue
1 x Baseload @ 2.1 GW fm GEO	@ $14.52 B	100 %	$2,846 M
DRM 5a	Installed Cost	"Platform Margin"	Reserve / Revenue
100 x Baseload @ 2.1 GW fm GEO	@ $10.94 B	100 %	$1,049 M

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100 x Baseload @ 2.1 GW fm GEO	@ $10.94 B	100 %	$1,049 M

SPS-ALPHA Design Reference Missions – DRM 1

Overview (CR = 1:1; Lifetime ≤ 1 year)			
Platform Mass	Dry Mass	kilograms	3,810 kg
Platform Power on Orbit	RF Power Output	kilowawtts	~19.66 kW
Platform Power Delivered to Earth	Power to "Grid"	kilowatts	N/A
Platform Array / Transmitter	Diameter	meters	8.50 m
Ground Systems	Demo / Communications	Diameter (km)	N/A
Platform Installed Cost	Initial Cost in Orbit	$, M	$ 116 M
Levelized Cost of Electricity (LCOE)	LCOE in Orbit	¢ / kW-hour	N/A
Platform Hardware Specific Cost	H/W Cost per Mass	$ / kg	$ 22,423 / kg
Specific Cost of Launch to LEO	Launch Cost per Mass	$ / kg	$ 5,000 / kg
Operations (Space & Ground)	Annual Ops Cost	$ / Year	≤ $1M

Platform Summary	Primary Modules	Segment Mass	%
Power Generation / Transmitter Array	WPT, SPG, ICs (Type 1), Bus Modules	1,628 kg	~45 %
Primary "Backbone" / Frame Structures	ICs (Type 1), Frames (Type 1 & Type 2)	1,022 kg	~28 %
Reflector Array / Reflectors	ICs (Type 2), Frames (Type 1 & 2), Reflectors, Robotics	492 kg	~13 %
Active Operations Support Systems	Robotics, WiFI, Communications, Propulsion, AR&D, Kernel	520 kg	~14 %

SPS-ALPHA Design Reference Missions – DRM 2a

Overview (CR = 2:1; Lifetime ≤ 30 years)			
Platform Mass	Dry Mass	kilograms	8,470 kg
Platform Power on Orbit	RF Power Output	kilowawtts	~107 kW
Platform Power Delivered to Earth	Power to “Grid”	kilowatts	N/A
Platform Array / Transmitter	Diameter	meters	14.0 m
Ground Systems	Demo / Communications	Diameter (km)	N/A
Platform Installed Cost	Initial Cost in Orbit	$, M	$153 M
Levelized Cost of Electricity (LCOE)	LCOE in Orbit	$ / kW-hour	$6.50 / kWh
Platform Hardware Specific Cost	H/W Cost per Mass	$ / kg	$11,080 / kg
Specific Cost of Launch to GTO	Launch Cost per Mass	$ / kg	$1,400 / kg
Operations (Space & Ground)	Annual Ops Cost	$ / Year	≤ $3 M / year
Platform Summary	Primary Modules	Segment Mass	%
Power Generation / Transmitter Array	WPT, SPG, ICs (Type 1), Bus Modules	4,233 kg	~50.0 %
Primary ”Backbone” / Frame Structures	ICs (Type 1), Frames (Type 1 & Type 2)	1,723 kg	~20.3%
Reflector Array / Reflectors	ICs (Type 2), Frames (Type 1 & 2), Reflectors, Robotics	939 kg	~11.1 %
Active Operations Support Systems	Robotics, WiFI, Communications, Propulsion, AR&D, Kernel	1,575 kg	~18.6 %

SPS-ALPHA Design Reference Missions – DRM 3

Overview (CR = 3:1; Lifetime ≤ 30 years)			
Platform Mass	Dry Mass	Metric Tons	9.201 MT
Platform Power on Orbit	RF Power Output	Megawatts	2.52 GW
Platform Power Delivered to Earth	Power to “Grid”	Megawatts	2.08 GW
Platform Array / Transmitter	Diameter	meters	1,740 m
Ground Systems	Rectenna	Diameter (m)	6,100 m
Platform Installed Cost	Initial Cost in Orbit	$, M	$10.94 B
Levelized Cost of Electricity (LCOE)	LCOE in Orbit	$ / kW-hour	2.5 ¢/ kWh
Platform Hardware Specific Cost	H/W Cost per Mass	$ / kg	$228 / kg
Specific Cost of Launch to GTO	Launch Cost per Mass	$ / kg	$600 / kg
Operations (Space & Ground)	Annual Ops Cost	$ / Year	≤ $100 M / yr

Platform Summary	Primary Modules	Segment Mass	%
Power Generation / Transmitter Array	WPT, SPG, ICs (Type 1), Bus Modules	6,600 MT	~71.7 %
Primary ”Backbone” / Frame Structures	ICs (Type 1), Frames (Type 1 & Type 2)	1,020 MT	~11.1 %
Reflector Array / Reflectors	ICs (Type 2), Frames (Type 1 & 2), Reflectors, Robotics	1,290 MT	~14.0 %
Active Operations Support Systems	Robotics, WiFI, Communications, Propulsion, AR&D, Kernel	39 MT	~4.2 %

SPS-ALPHA Design Reference Missions – DRM 5a

Overview (CR = 3:1; Lifetime ≤ 30 years)			
Platform Mass	Dry Mass	Metric Tons	9.201 MT
Platform Power on Orbit	RF Power Output	Megawatts	2.52 GW
Platform Power Delivered to Earth	Power to “Grid”	Megawatts	2.08 GW
Platform Array / Transmitter	Diameter	meters	1,740 m
Ground Systems	Rectenna	Diameter (m)	6,100 m
Platform Installed Cost	Initial Cost in Orbit	$, M	$10.94 B
Levelized Cost of Electricity (LCOE)	LCOE in Orbit	$ / kW-hour	2.5 ¢/ kWh
Platform Hardware Specific Cost	H/W Cost per Mass	$ / kg	$228 / kg
Specific Cost of Launch to GTO	Launch Cost per Mass	$ / kg	$600 / kg
Operations (Space & Ground)	Annual Ops Cost	$ / Year	≤ $100 M / yr
Platform Summary	Primary Modules	Segment Mass	%
Power Generation / Transmitter Array	WPT, SPG, ICs (Type 1), Bus Modules	6,600 MT	~71.7 %
Primary ”Backbone” / Frame Structures	ICs (Type 1), Frames (Type 1 & Type 2)	1,020 MT	~11.1 %
Reflector Array / Reflectors	ICs (Type 2), Frames (Type 1 & 2), Reflectors, Robotics	1,290 MT	~14.0 %
Active Operations Support Systems	Robotics, WiFI, Communications, Propulsion, AR&D, Kernel	39 MT	~4.2 %

Summary & Conclusions

- There is an urgent need for new & sustainable (i.e., zero net Carbon) energy sources that can be scaled during the coming decades to deliver TW of power globally
- Space Solar Power is one of the possible sources for this energy – and it requires no technical breakthroughs to be realized
- An updated version of the concept of the Solar Power Satellite via Arbitrarily Large Phased Array – “SPS-ALPHA Mark-II” – has been developed
- SPS-ALPHA Mark-II promises to deliver electricity at an LCOE below 3¢ per kilowatt-hour with advanced ETO infrastructure, and below 10¢ / kWh with systems that are available today…
- Time is short; the world needs to begin now to develop an array of novel energy solutions to meet the requirements of humanity for the future