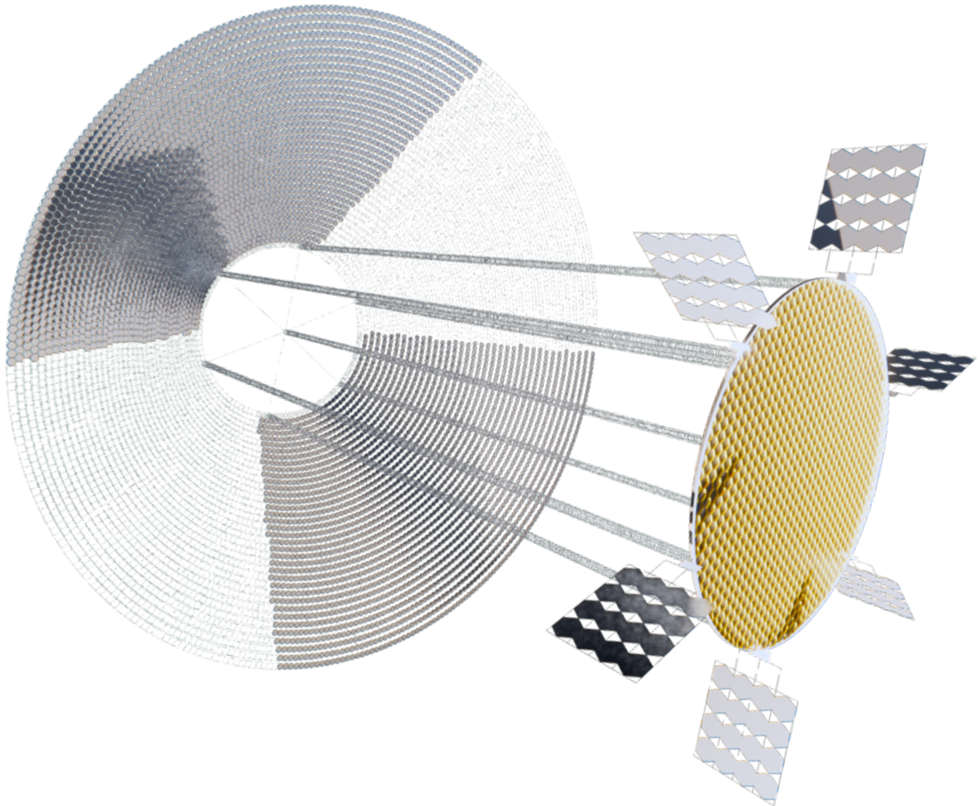

Space Solar Power: An Overview

26 May 2022

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Chair, IAA Space Solar Power Permanent Committee
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Board Member at Large, National Space Society

Outline

- Introduction
- History
- Selected critical advances since the 1980s
- Comparison of Leading Approaches to Space Solar Power
- Programmatic Activities
- Hyper-Modular SPS-ALPHA : some detailed numbers
- Summing up

Why are Novel Energy Solutions important…?
urgent need to solve Carbon Net-Zero challenge for the World …

We must transition more than ~3 Billion individuals in "current economies" to net-zero carbon energy by 2050

AND

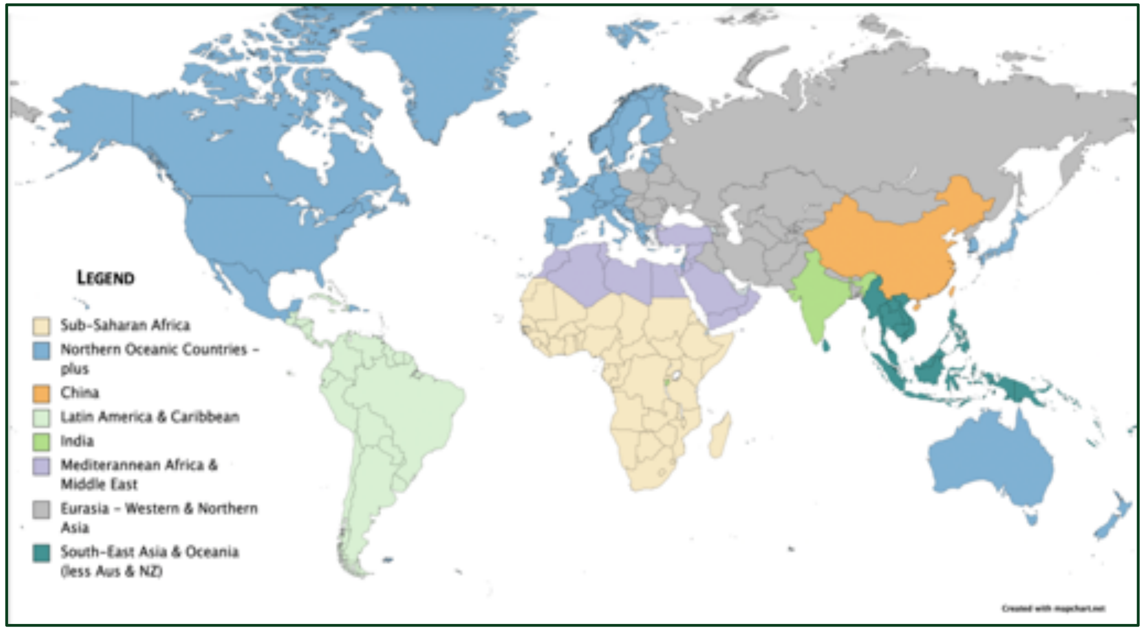
Provide Sustainable Energy to an additional ~6 Billion in "emerging economies" during this Century

EURASIA (Western & Northern Asia)
Population Today: 0.93 Billion
Energy Today : 19,100-kWh/person
Population in 2100: 1.1 Billion

CHINA
Population Today: 1.47 Billion
Energy Today : 26,500-kWh/person
Population in 2100: ~1.09 Billion

NORTHERN OCEANIC
Population Today: 1.03 Billion
Energy Today : 58,000-kWh per person
Population in 2100: 1.1 Billion

LATIN AMERICA & CARRIBEAN
Population Today: 0.65 Billion
Energy Today : **11,000-kWh** per person
Population in 2100: 0.68 Billion



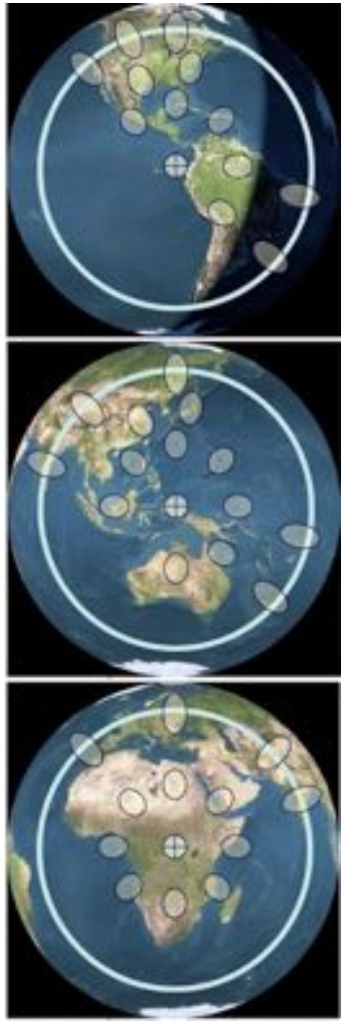
INDIA
Population Today: 1.45 Billion
Energy Today : **7,800-kWh** per person
Population in 2100: 1.45 Billion

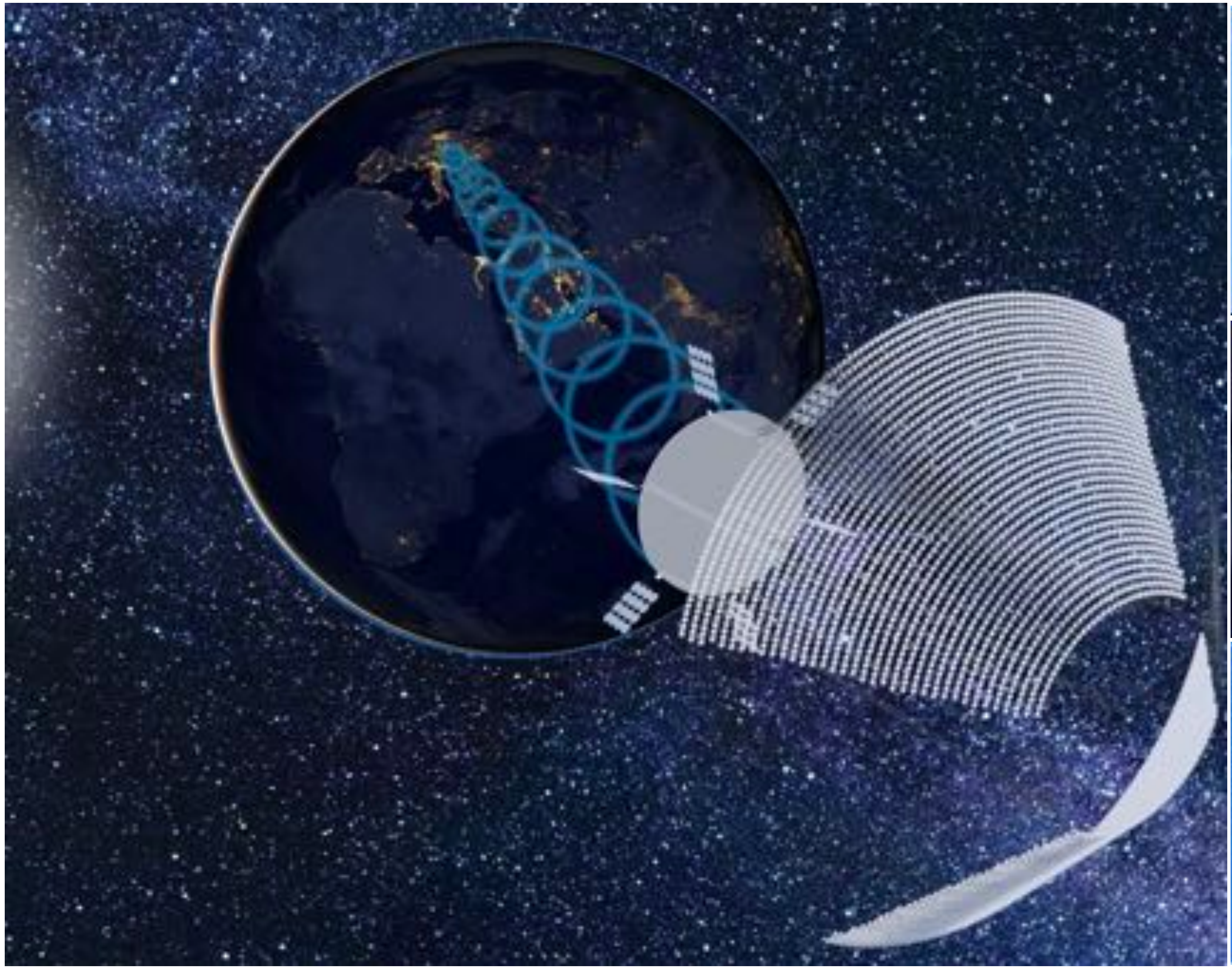
SOUTH-ASIA & OCEANIA
Population Today: 0.71 Billion
Energy Today : **14,600-kWh** per person
Population in 2100: 0.79 Billion

SUB-SAHARAN AFRICA
Population Today: 1.09 Billion
Energy Today : **5,900-kWh/**person
Population in 2100: 3.7 Billion

MEDITTERANEAN AFRICA & MIDDLE EAST
Population Today: 0.53 Billion
Energy Today : 27,500-kWh/person
Population in 2100: 0.93 Billion

The Vision of Space Solar Power





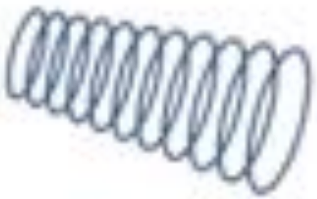
How Would Space Solar Power Work?

THE SUN

- Can power 2,880 trillion light bulbs
- 1.4 million kilometer diameter
- The Sun has enough hydrogen fuel for billions of years

SPS-ALPHA SPACE-BASED HARVESTING

- ~6 km reflector array
- ~1.8 km solar PV panels + wireless power transmitter array
- ~7 km backbone structure
- Modular, robotic construction
- Cheap to launch; less than $1,000/kg
- 99.95% Available Power



MICROWAVE ENERGY TRANSFER

- Precisely controlled transmission of energy
- Less than 20% of summer sunlight
- Can be “shared” across receivers and coordinated with ground-based solar

GROUND STATION

- ~6km diameter (elevated 5-10 m)
- Outside metro areas
- Mesh RF ‘Rectifying Antenna’ system
- Uses batteries to modulate supply to the existing electricity grid

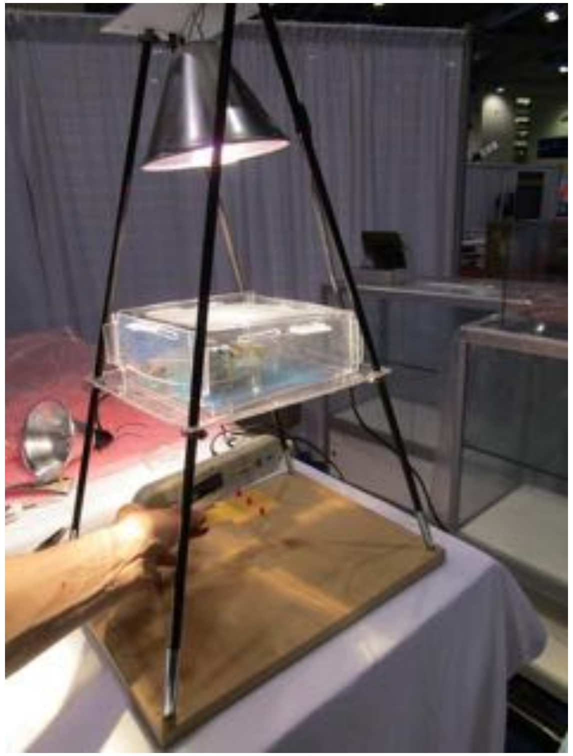
EXISTING INFRASTRUCTURE

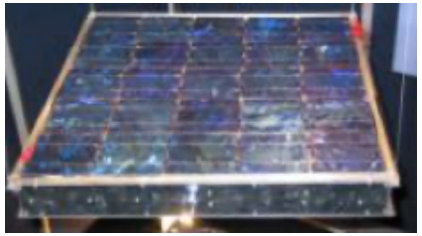
- DC or AC fed into the local grid
- Resembles Hydroelectric Power – but…
- “Always” available
- “Shareable” across markets

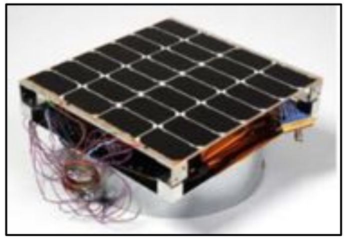
HOMES AND BUSINESSES

- Base Load low cost electricity
- No carbon emissions
- Supports use at all hours of the day

End-to-End Demonstrations of SSP Energy Conversion Physics







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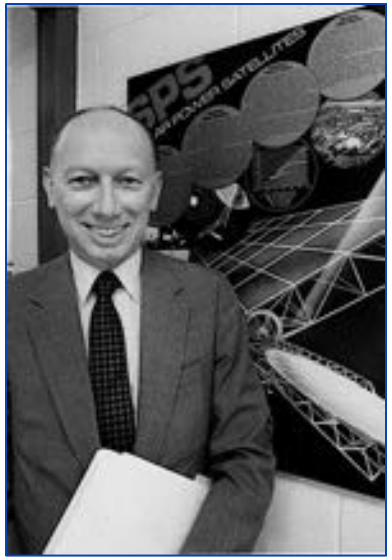
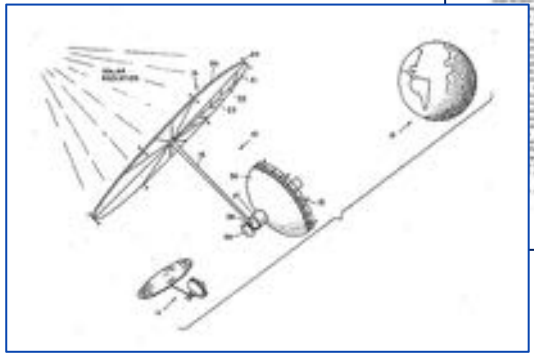
1940s-1960s

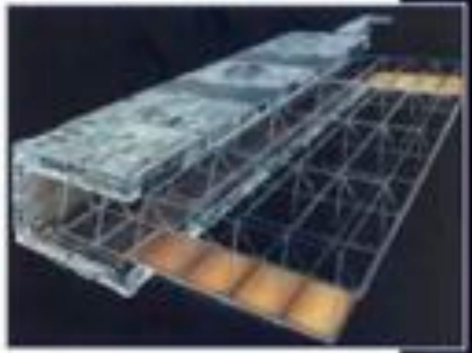


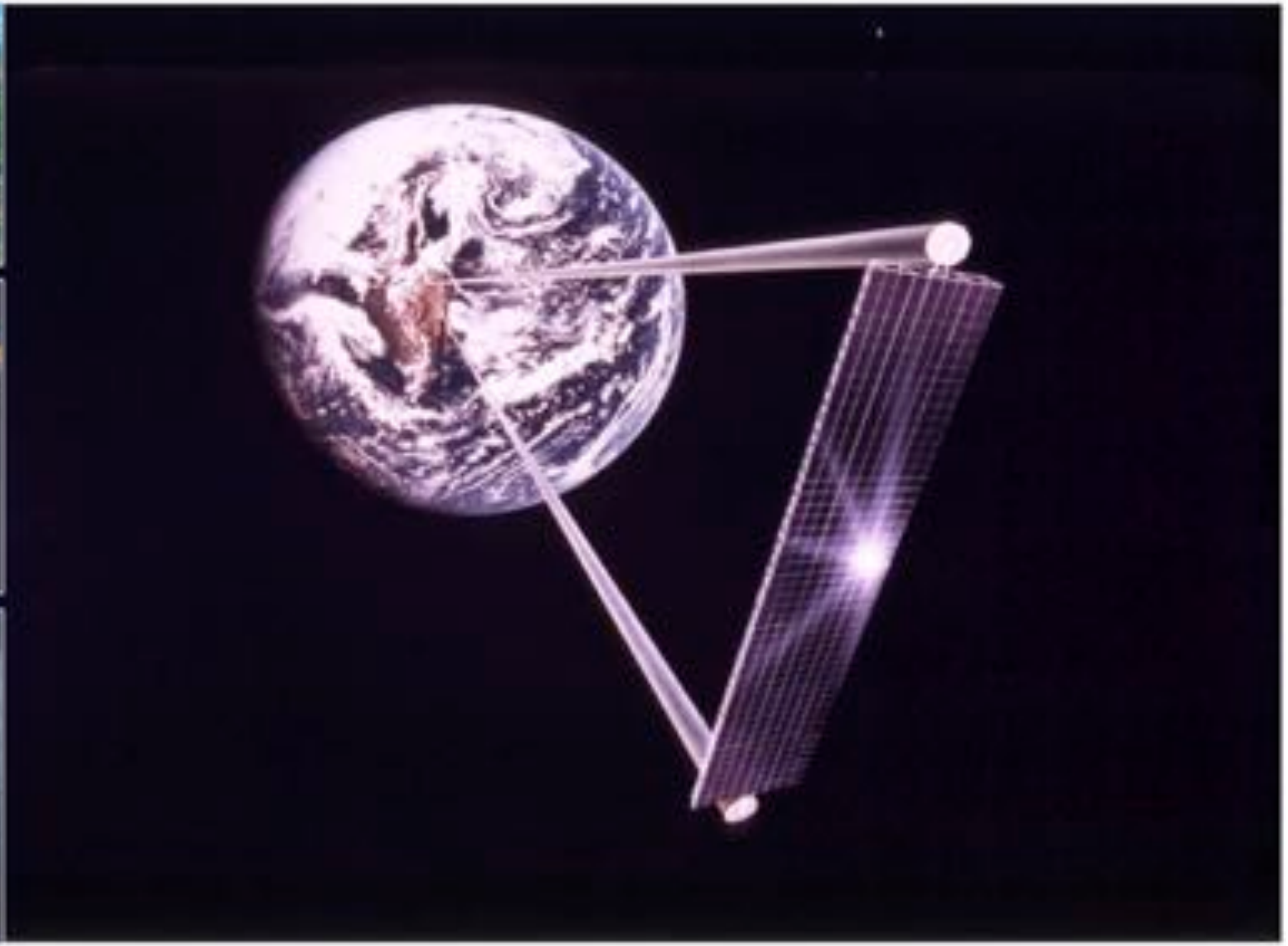

SCIENCE

Power from the Sun: Its Future

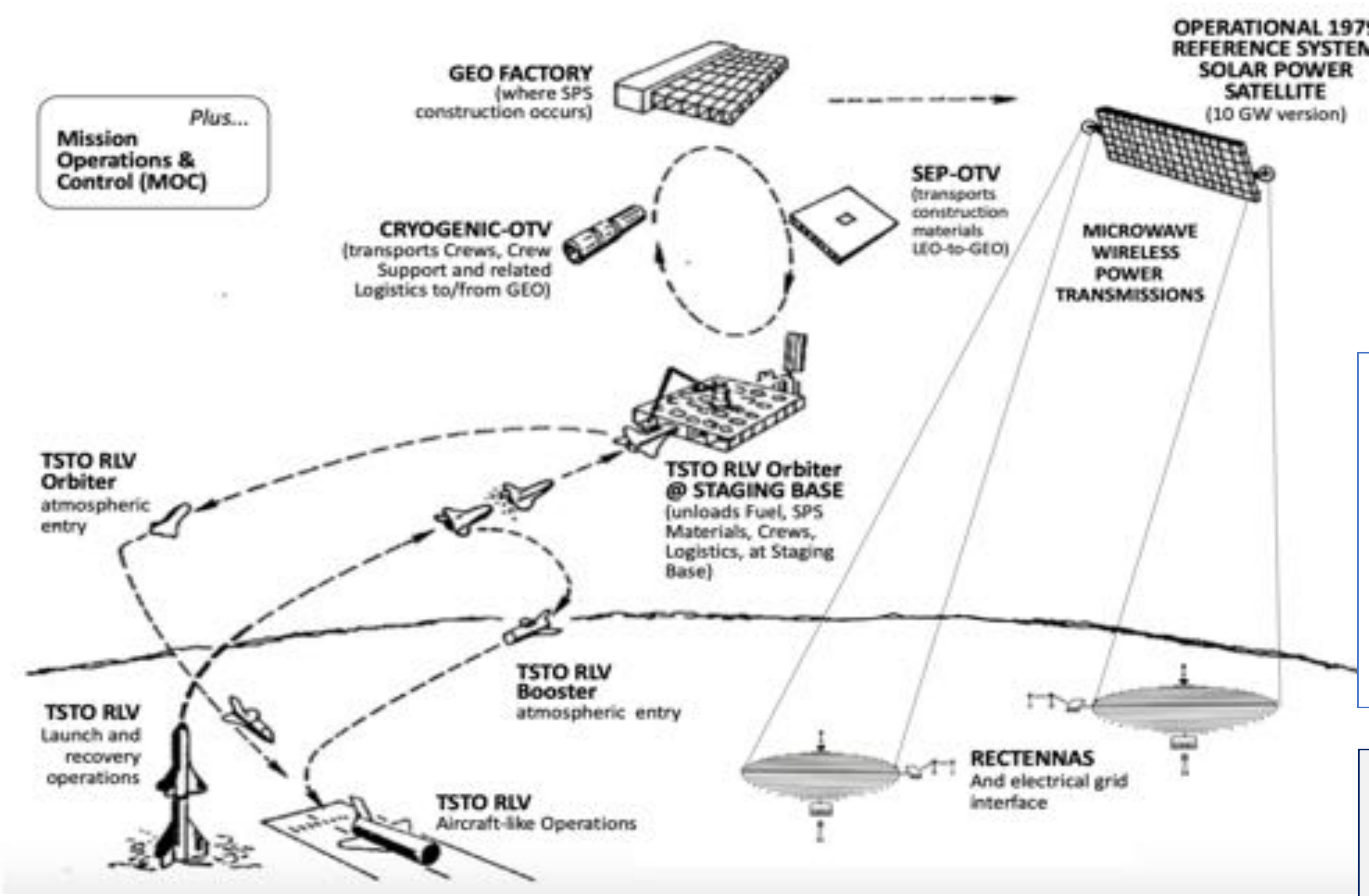


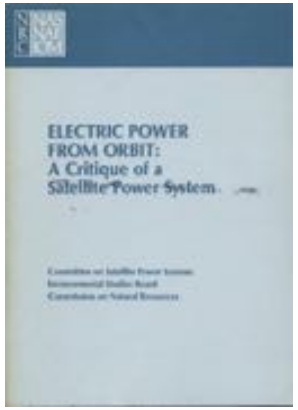
1970s-1980s

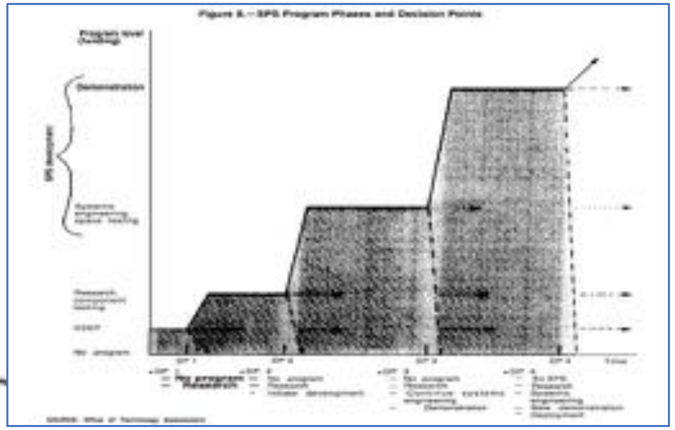




1979 Reference System - CONOPS

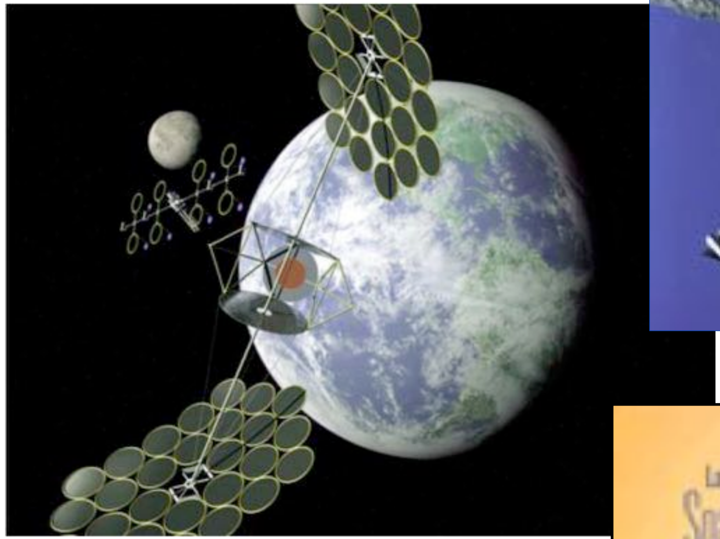


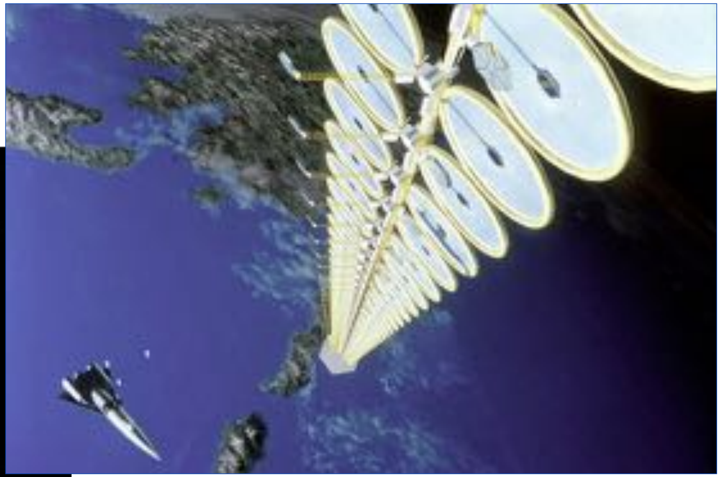


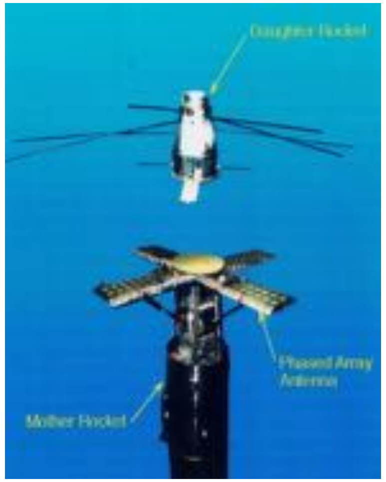


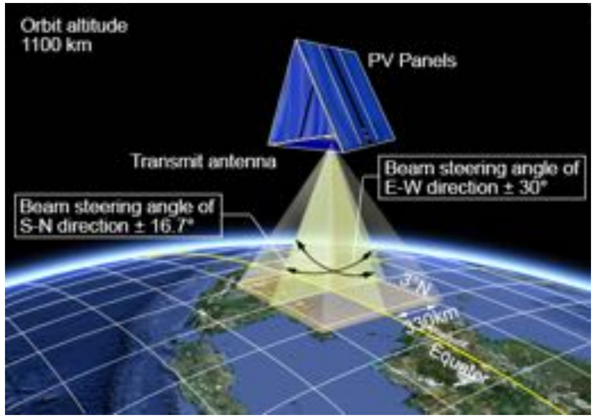
Using 1976 Technology
Roughly 20 years &
$1,000 B to "First kW-hr"

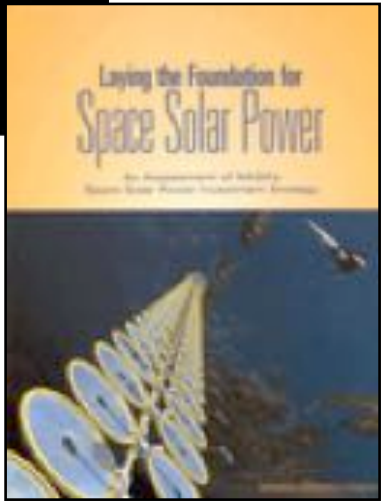
c. 1990 to c. 2015

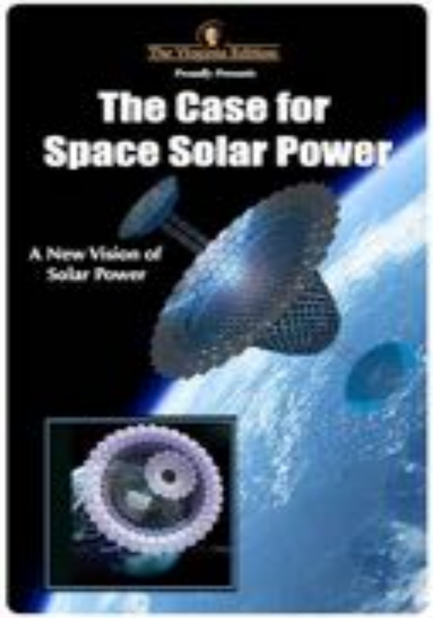












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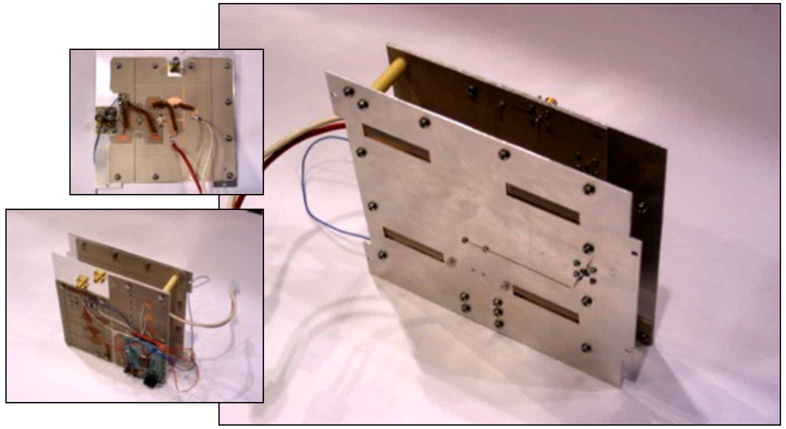
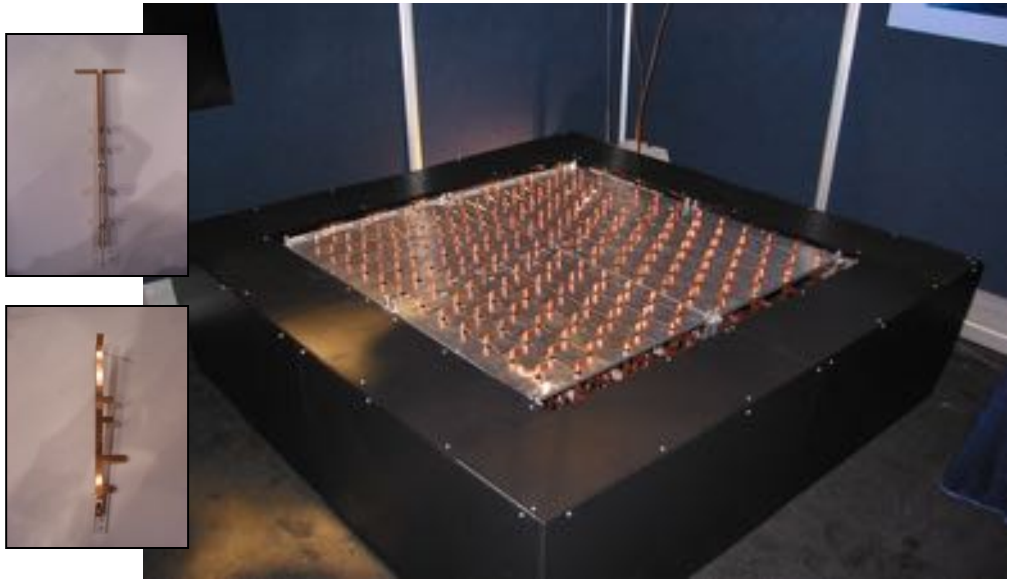
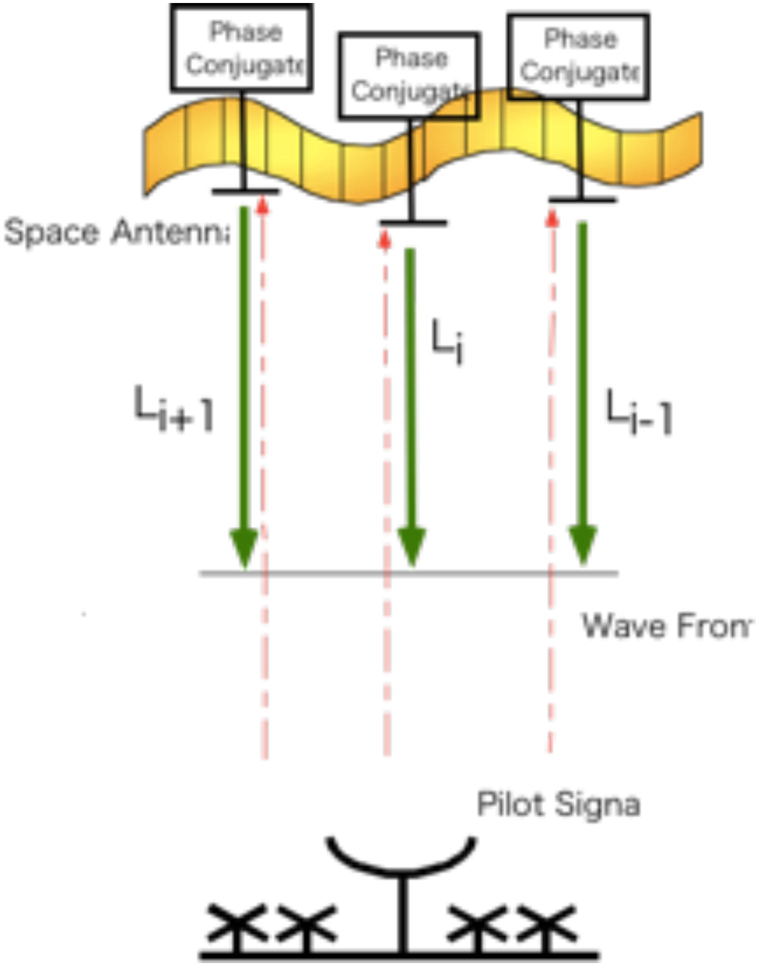
Since 1980, multiple revolutionary advances...

- High-efficiency PV (30%-plus versus 10%)
- High-efficiency solid-state power amplifiers versus electron tubes (up to 70%-80% vs. 20%)
- Tele-supervised / semi-autonomous / automated robotics
- Low-mass, deployable reflectors
- Information, Not Structure
- Low-cost launch
- Low-cost / mass produced space systems

Trading Information for Mass:
Retrodirective Phased Arrays and Flexible Structures

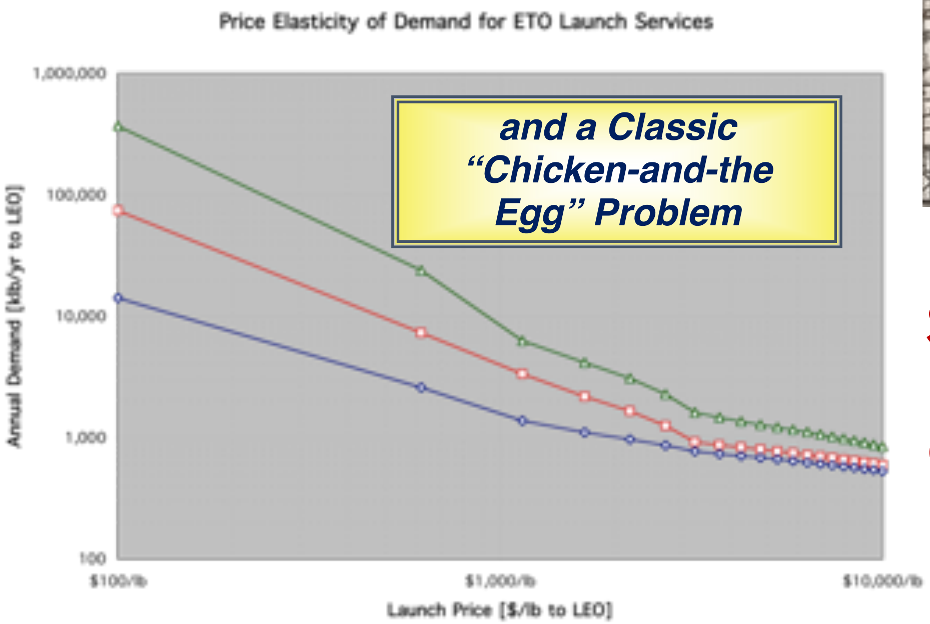






Realizing Low Cost Space Launch

Past
Since ~1960s…
LEO Launch Cost
@ < $20,000/kg



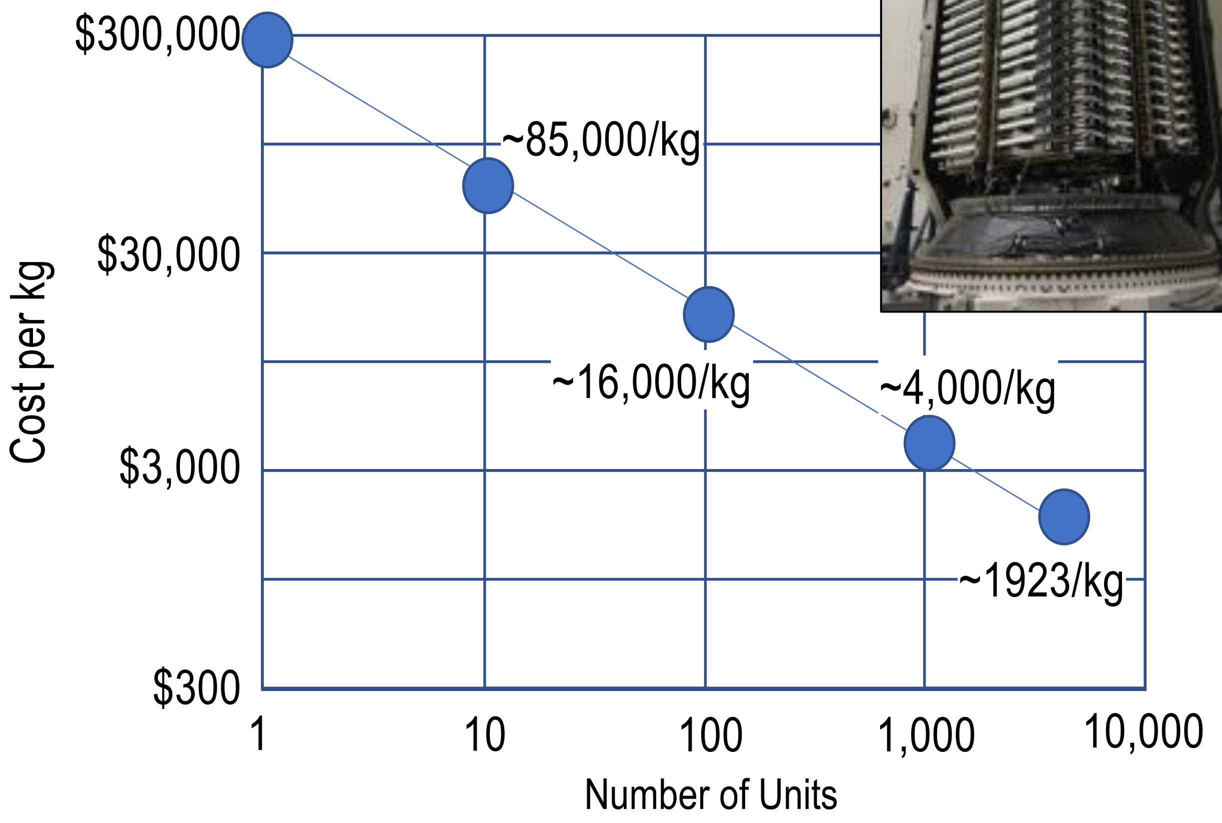
Present
Since 2015…
LEO Launch Cost
@ < $2,000/kg
Reduction >90%

Future
After ~2025 (?)…
LEO Launch Cost
@ ~ $100/kg to LEO
Reduction: >99%

Mass Production of Space Systems

- Description
  - Initial Constellation: 4,400 Satellites
  - RF Satellites
  - Solar-powered (@ ~5 kW)
  - Dry Mass: @ 260 kg
  - @ $500,000 each)
- Manufacturing Capacity:
  - @ 120 Satellites / Month
  - @ ~30 MT / Month
- Estimated Development "CER"
  - ~$200K – $300K / kg
  - Estimated Manufacturing Curve: ~0.7

HW Cost Reduction: >99%



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Creating a Taxonomy for Solar Power Satellites (Design, Technology, CONOPs…)

- Critical Characteristics for Solar Power Satellite Platforms?
  - Frequency / type of power delivery from space to ground?
  - Voltage/Scale of the power management and distribution (PMAD) system
  - Use of rotary systems: with / without PMAD? Scale?
  - Active thermal or not?
  - Type of structural system: ‘stick built’? large modular? thin-film?
  - Robotic assembly or kinematically deployed structural systems?
  - Type of solar power generation (SPG): PV, dynamic, solar-pumped, mirrors?
  - SPG input: solar redirection using Reflectors or not? Large single mirror or smaller heliostats?
  - One platform or more? Physically connected or not?

SPS Taxonomy (1 of 2)

Space Solar Power Major Platform Concepts Taxonomy

Type 1

- Single Platform
- Sun-pointing PV
- Large HV PMAD
- Rotating PMAD-WPT
- Active Thermal
- Nadir µwave WPT
- No Optics
- Propulsive ACS

1979 Ref. SPS
(US | DOE & NASA)

Type 2

- Single Platform
- Sun-Pointing PV
- Multiple Rotating PV-PMAD
- Large HV PMAD
- Active Thermal
- Fixed PMAD & Nadir µwave WPT
- PV Optics Option
- Propulsive ACS

Multi-Rotating Joint
(China | CAST)
Sun Tower / Sail Tower
(US | NASA)
Multiple Array Central Transmitter
Korea / KARI

Type 3

- Multi-segment Platform
- Sun-Pointing PV
- Moderate HV PMAD
- Active Thermal
- WPT Optics
- Highly Modular Structure
- Laser WPT
- Propulsive ACS

Modular Electric Laser SPS
(US | Aerospace)

Type 4

- No Moving Parts
- Single Platform
- Sandwich Panel
- PV-PMAD-WPT
- No Optics
- Nadir µwave WPT
- Precision Assembly
- (Robotics or AR&D)
- Gravity Gradient & Propulsive ACS

"Simple" Integrated Sandwich Module SPS
(Japan)

Type 5

- No Moving Parts*
- Many Platforms
- Thin-film Sandwich PV-PMAD-WPT
- Local Optics
- Kinematic Structure & *Deployment
- (no Robotics)
- Varying µwave WPT
- Precision Propulsive Maneuver

Single-Substrate Thin-Film SPS Swarm
(US | CIT-NG)

Type 6

- Single Platform
- 'Modular Panel'
- PV-PMAD-WPT
- Large Reflector / Array
- Active Thermal (SPS-OMEGA Only)
- Large Highly-Modular Structure
- w/ Robotic Assembly
- Nadir WPT
- Gravity Gradient & Propulsive ACS

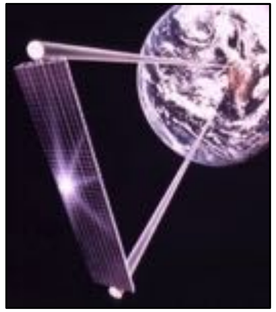
SPS-ALPHA
(US | MSTI)
Cassiopeia
(UK | Cash)
SPS-OMEGA
(China | Cash)

Special Technical Challenges

SPS Taxonomy
2 of 2

Space Solar Power Major Platform Concepts Taxonomy

Type 1

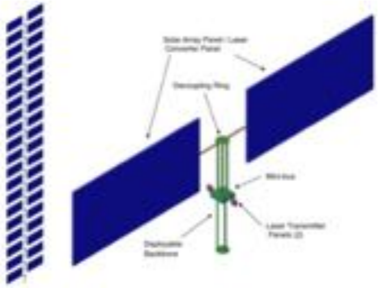


1979 Ref. SPS
(US | DOE & NASA)

Type 2

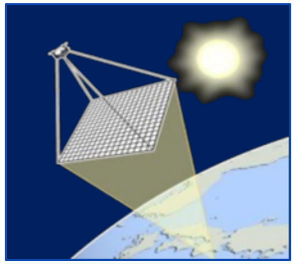
Multi-Rotating Joint
(China | CAST)
Sun Tower / Sail Tower
(US | NASA)
Multiple Array Central Transmitter
Korea / KARI

Type 3



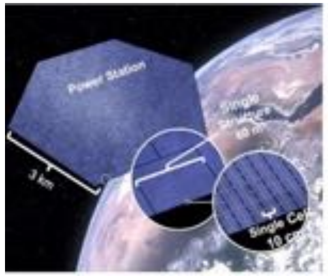
Modular Electric Laser SPS
(US | Aerospace)

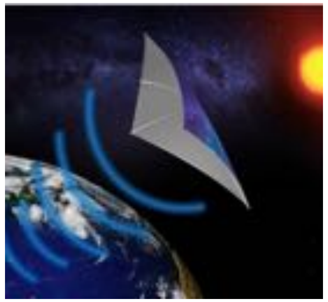
Type 4



"Simple" Integrated Sandwich SPS
(Japan)

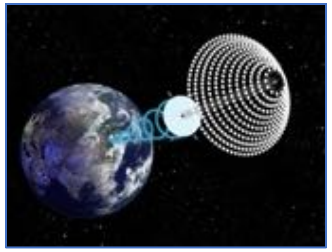
Type 5

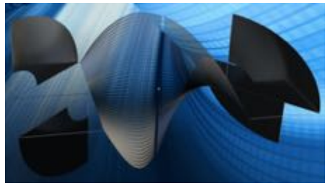


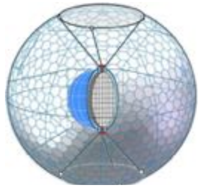


Single-Substrate Thin-Film SPS Swarm
(US | CIT-NG)

Type 6





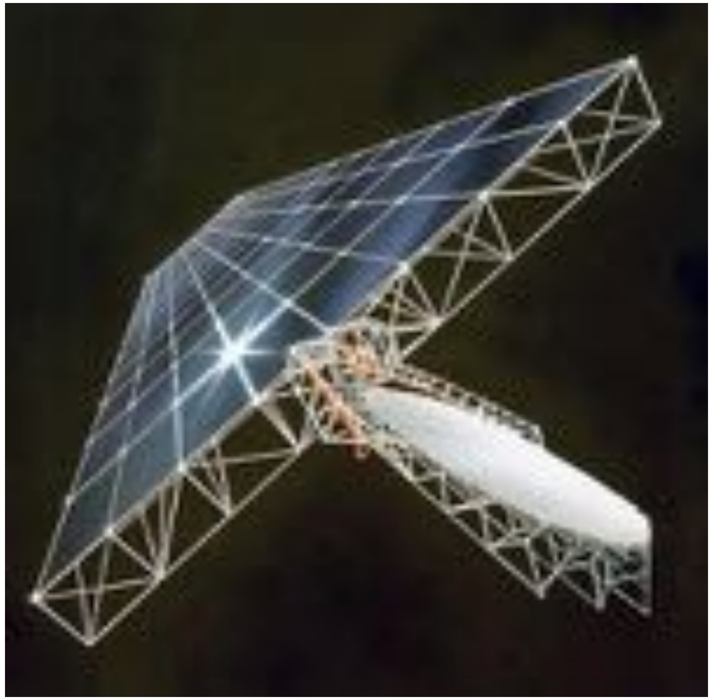


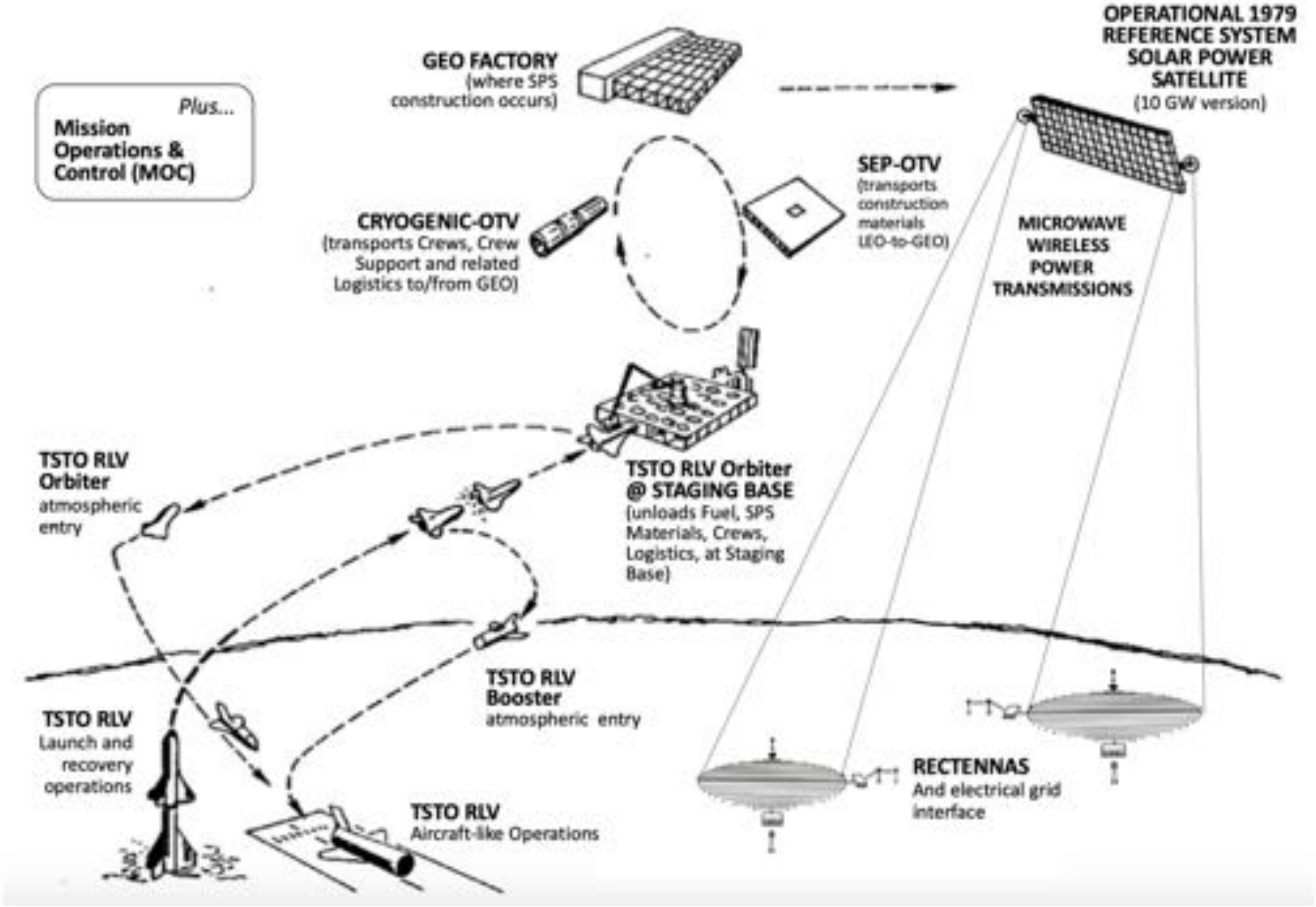
SPS-ALPHA
(US | MSTI)
Cassiopeia
(UK | CASH)
SPS-OMEGA
(China | CASH)

Comparison of SPS Options: Common **Assumptions**

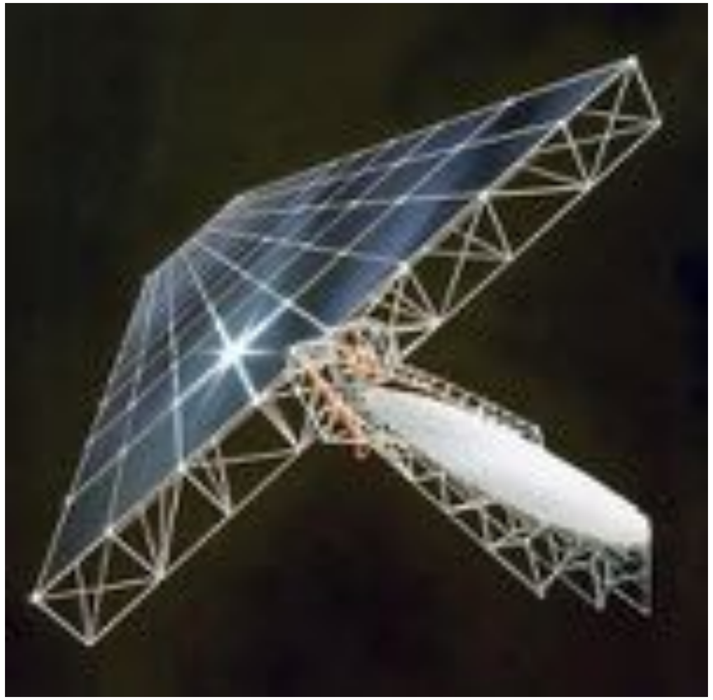
- Power Delivered to Grid @ 2 GW
- Lifetime: @ 30 years
- Total Energy Delivered (24/7 Cases): ~525,960,000,000 kWh
- Cost of Transport @ $200 / kg (= Starship+Heavy Booster x 2)
- Operations in GEO (35,000 km distance for power transmission)
- Operations & Maintenance @ 3% of capital cost per year
- Cost of Money @ 5% / year
- Cost of in-space infrastructure to be used for 300 GW total SPS power delivered
- Cost of Receiver is the same for all SPS concepts, *and* small compared to space segment

1979 SPS Reference Concept – USA (DOE / NASA) / 2015 SPS Type 1 | CONOPS





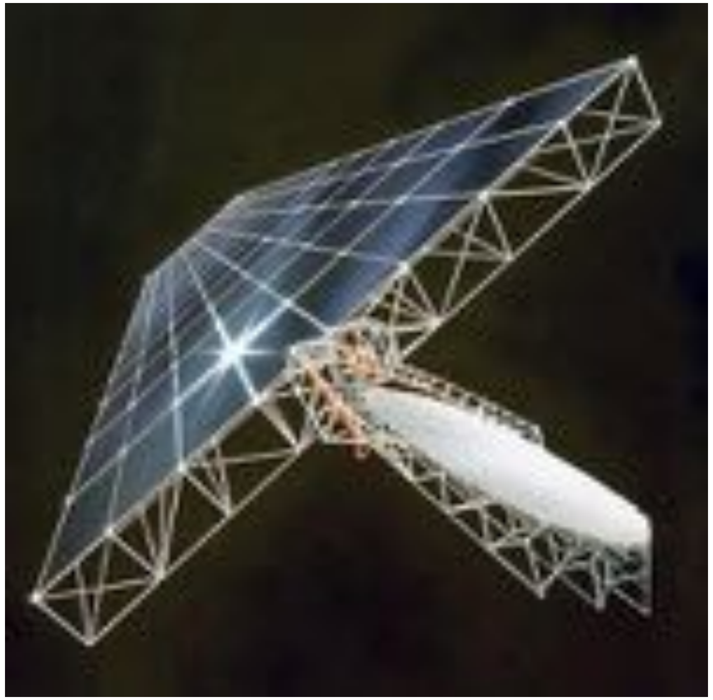
1979 SPS Reference Concept – USA (DOE / NASA) | 1978 SPS Type 1 | Summary Assessment



PROS:
- Relatively simple architectural solution
- highly similar to conventional spacecraft
- Uses ISS-derived in-space infrastructure

CONS:
- Highly challenging development program
- Factories in LEO and GEO required (Concept requires astronaut EVA for construction
- 3 ETO systems required (booster, cargo, crew)
- Minimally Modular architecture – high cost per module
- High technology risk high-voltage PMAD required (many 1,000s of meters)
  - ✓ Scaling-up requires redesign of PMAD / Thermal systems

1979 SPS Reference Concept – USA (DOE / NASA) | 1978
SPS Type 1 | Details & Normalization*



- Wavelength: 2.45 GHz
- Assumed Key Tech:
  - PV @ 10% (vs. 20% for Normalized case)
  - PMAD @ ~85%
  - WPT @ (2.45 GHz)
    - ✓ 80% Transmitter (magnetron)
    - ✓ 90% Rectenna
- Assessed Modularity:
  - Low...
  - ~10 MT / module
- Power Availability:
  - 99.95% @ 24 / 7
- Major In-Space Infrastructure
  - SEPS / Cryo OTVs
  - Space Stations for Workers
  - Factories (LEO & GEO)

	Baseline	Normalized
Power Delivered	~10 GW	~2 GW
Transmitter Diam (km)	2 * 1 km	~ 1 km
Max SPS Dimension (km)	20 km	10 km
SPS Mass (MT)	~106,000 MT	~20,000 MT
SPS HW Cost ($)	$869 B	~ $160 B
Transport Cost ($/SPS)	$2,813 B /SPS	$4 B / SPS
Est Space Infra-structure Cost	$99 B / SPS	~$300 B / SPS
Est. System Cost	~$3,894 B	~$464 B
Est. O&M Cost	~$ 113B @ ~0.3% / yr	~$420 B @ 3% / year
Finance Cost	N/A	$696 B @ 5% / year
LCOE	~$1.48 / kWh	$3.00 / kWh

* *Note: since the 1979 study, the ISS and Space Shuttle programs have provided a better baseline cost estimate; the revised figures are used here.*

Multi-Rotary Joints (MRJ) Solar Power Satellite – China | 2015
SPS Type 2 | Summary Assessment

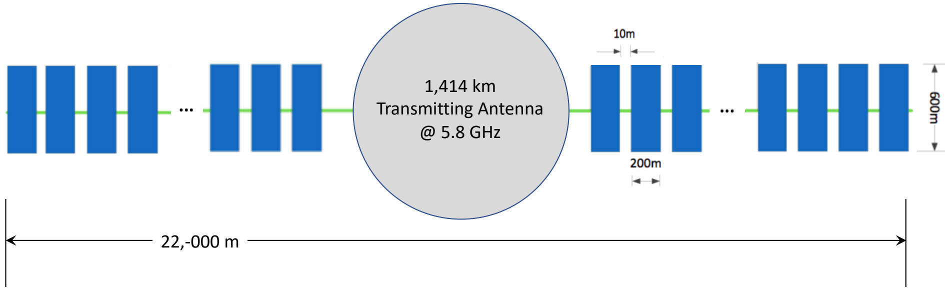
PROS:

- Relatively simple architectural solution; similar to others
- Minimal up-front space infrastructure
- Use of common launchers
- Selected highly modular elements (PV, WPT)

CONS:

- Challenging development
- Requires large structural system
- Partially Integrated / Partially Modular architecture – higher cost per module
- High-voltage PMAD required (many 1,000s of meters)
  - ✓ Scaling-up requires redesign of PMAD / Thermal systems
- Requires precision free-flying robotics for assembly

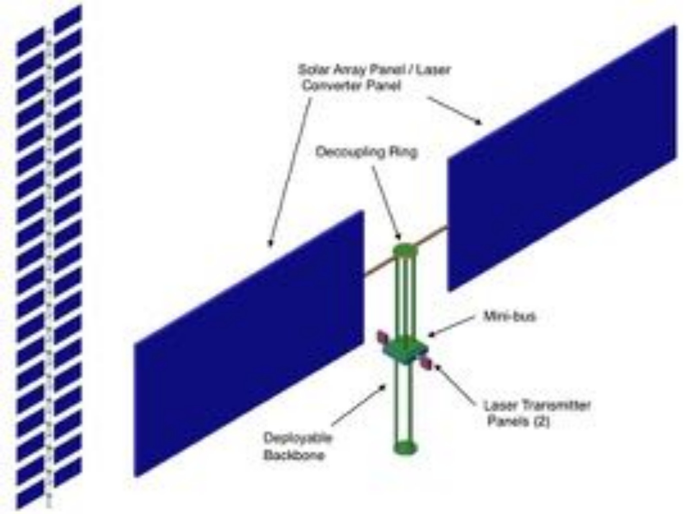
Multi-Rotary Joints (MRJ) Solar Power Satellite – China | 2015
SPS Type 2 | Details and Normalization

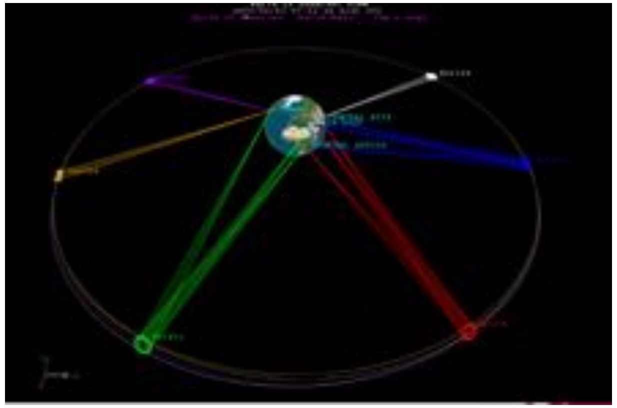


- Wavelength: 5.8 GHz
- Assumed Key Tech:
  - PV @ 30%
  - PMAD @ 85%
  - WPT @ (5.8 GHz)
    - 85% Transmitter (solid state)
    - 90% Rectenna
- Assessed Modularity:
  - Moderate
  - ~1 MT / module
- Power Availability:
  - 99.95% @ 24 / 7
- In-Space Infrastructure
  - SEPS OTVs
  - Free-flying robotics

	Baseline	Normalized
Power Delivered	~1 GW	~2 GW
Transmitter Diam (km)	~ 1 km	~ 1.4 km
Max SPS Dimension (km)	11.8 km	22 km
SPS Mass (MT)	10,000	20,000
SPS HW Cost ($)	$9.1 B	~ $18.2 B
Transport Cost ($/SPS)	$10 B / SPS	$4 B / SPS
Est Space Infra-structure Cost	$3.8 B/SPS	$7.6 B / SPS
Est. System Cost	~$28 B	~$30 B
O&M Cost	~$4 B @ ~0.7% / yr	~$27 B @ 3% / year
Finance Cost	~$36 B	~$45 B @ 5% / year
LCOE	~24¢ / kWh	$19¢ / kWh

Modular Electric Laser Solar Power Satellite – USA | 2000
SPS Type 3 | Summary Assessment





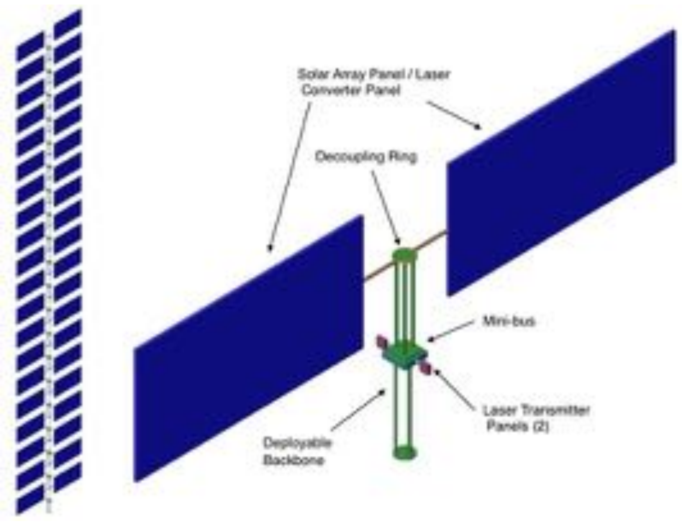
PROS:

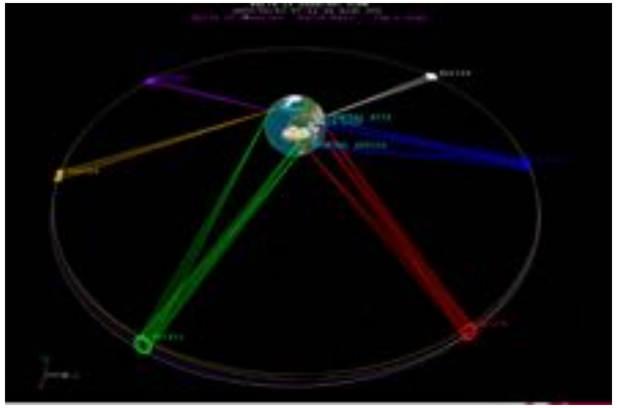
- Lowest cost for entry to deliver power from GEO
- No in-space assembly robotics or infrastructure required

CONS:

- Low-to-medium Modularity architecture – higher cost per module
- High technology risk in optical systems required
- Partially Integrated / Partially Modular architecture – higher cost per module
- High-voltage PMAD required (many 1,000s of meters)
  - ✓ Scaling-up requires redesign of PMAD / Thermal systems
- Requires precision free-flying robotics for assembly

Modular Electric Laser Solar Power Satellite – USA | 2000
SPS Type 3 | Details & Normalization



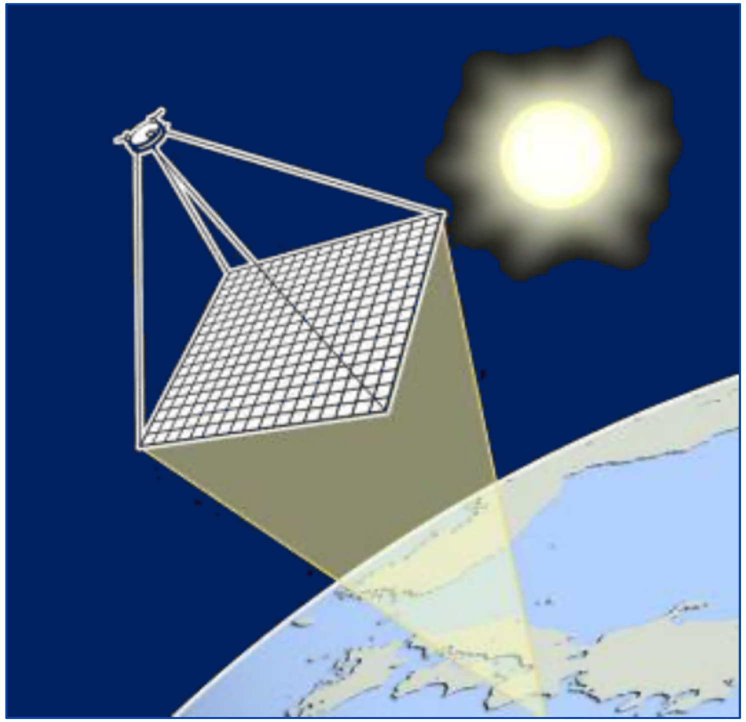


Note: HW costs from source questionable; normalized estimate based on HST / JWST

- Wavelength: near-Visible
- Assumed Key Tech:
  - Lifetime: 20 years (baseline)
  - PV @ 20%~30% efficiency
  - PMAD @ ~90%
  - WPT @ (Laser)
    - 60% Xmittr (solid state + Fiber + Optics)
    - 80% Atmospheric Absorption
    - 60% Tailored PV
- Assessed Modularity:
  - Low-to-Moderate
  - ~23,000 kg / module
- Power Availability:
  - ~65% of 99.95% (During Clear Weather; depends on location)
- Major In-Space Infrastructure: N/A
  - Not Required

	Baseline	Normalized
Peak Power Delivered	~1.2 GW	~2 GW
Transmitter Diam (km)	~3-5 m (single optics)	~3-5 m (single optics)
Max SPS Dimension (km)	~1 km	~1 km
SPS Mass (MT)	11,000 MT	~18,400 MT
SPS HW Cost* ($)	~$32 B*	~$110 B*
Transport Cost ($/SPS)	~$22 B /SPS	~$4 B / SPS
Est Space Infra-structure Cost	N/A	N/A
Est. System Cost	~$54 B	~ $114 B
Est. O&M Cost	N/A	~$102 B @ 3% / year
Finance Cost	N/A	$171 B @ 5% / year
LCOE	~40¢ / kWh (@ 20 yr Life)	74¢ / kWh (@30 yr Life)

Simple Planar SPS – Japan | 2010
SPS Type 4 | Summary Assessment



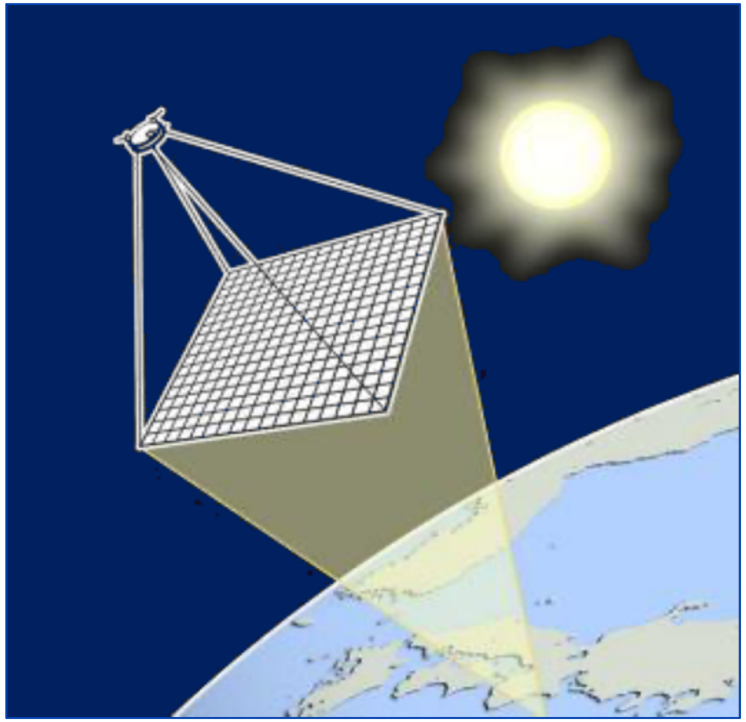
PROS:

- Very simple architectural solution; similar to others
- Very highly modular architecture
- Ease of ground-based testing
- Low-voltage PMAD
- Simple robotic assembly

CONS:

- Simplest development
- Daytime-only Power Generation @ ~25% per 24 hrs
- High estimated cost per kilowatt-hour for energy
- Requires large structural system
- Requires precision free-flying robotics for assembly

Simple Planar SPS – Japan | 2010
SPS Type 4 | Details & Normalization*

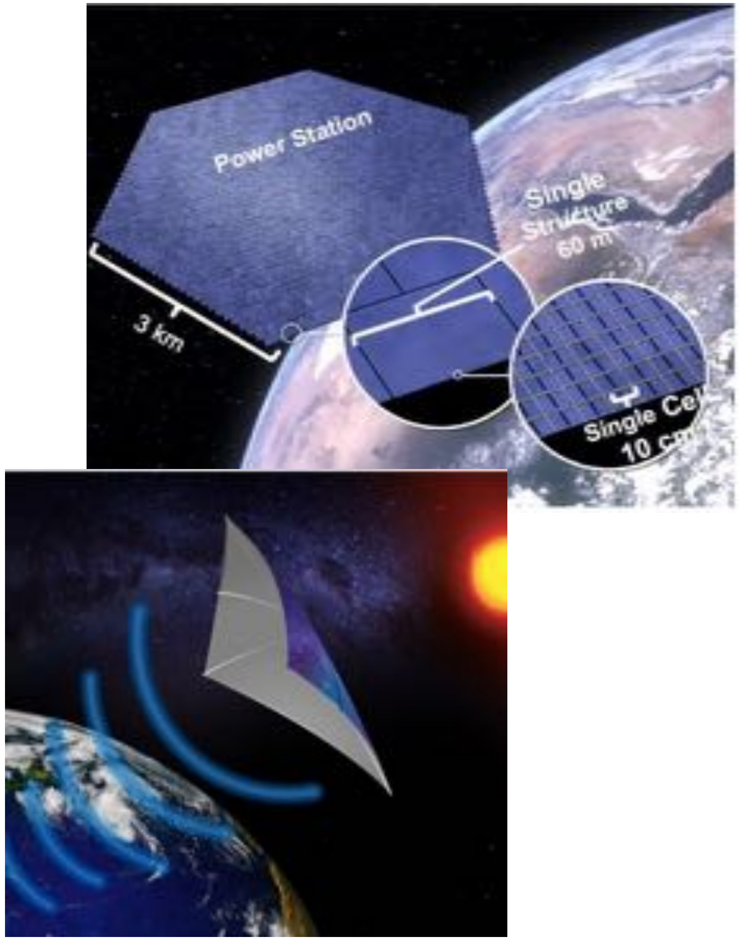


- Wavelength: 2.45 GHz
- Assumed Key Tech:
  - PV @ 20%
  - PMAD @ ~90%
  - WPT @ (2.45 GHz)
    - 70% Transmitter (solid state)
    - 85% Rectenna
- Assessed Modularity:
  - Very High
  - ~150 kg / module
- Power Availability:
  - ~25% @ 24/7
- Major In-Space Infrastructure
  - SEPS
  - Free-flying robotics

	Baseline	Normalized
Peak Power Delivered	~500 MW	~2 GW
Transmitter Diam (km)	~1 km	~ 2 km
Max SPS Dimension (km)	1 km	2 km
SPS Mass (MT)	4,700 MT	~18,800 MT
SPS HW Cost ($)	~$5 B	~$20 B
Transport Cost ($/SPS)	$4.7 B /SPS	~$4 B / SPS
Est Space Infra-structure Cost	~$4 B /SPS	~$4 B /SPS
Est. System Cost	~$14 B	~$28 B
Est. O&M Cost	N/A	~$25 B @ 3% / year
Finance Cost	N/A	$42 B @ 5% / year
LCOE	~ 42¢ / kWh	72¢ / kWh

* *Note: Robotics are estimated roughly...!*

Thin-Film Single Substrate SPS – USA | 2015
SPS Type 5 | Summary Assessment



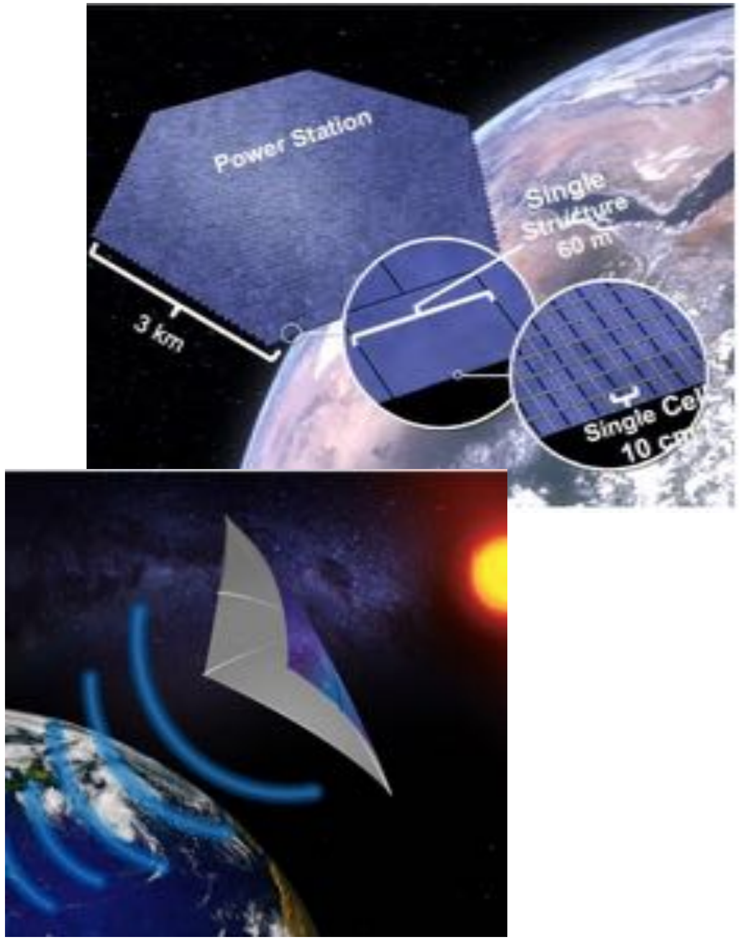
PROS:

- Lowest mass per square-meter
- “No” in-space assembly robotics or infrastructure required

CONS:

- Daytime-only Power Generation / ~40% per 24 hrs
- Low Modularity architecture – higher cost per module
- Requires large ‘flexible’ structural system
- Requires precision constellation with near-continuous attitude control / maneuvering required – but no definition
- Low efficiency for components on the thin-film material
- High-risk kinematically-deployed structural system
- Poor definition of refueling / in-space requirements

Thin-Film Single Substrate SPS – USA | 2015
SPS Type 5 | Details & Normalization*

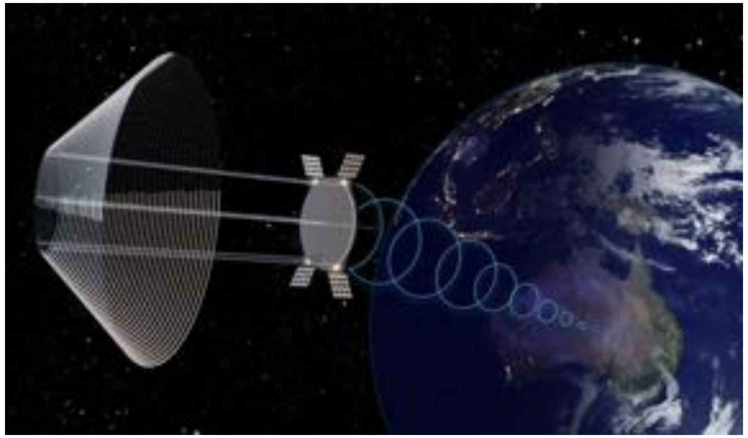


- Wavelength: 10 GHz
- Assumed Key Tech:
  - Lifetime: 15 years (baseline)
  - PV @ ~17%
  - PMAD @ ~100% (?)
  - WPT @ (10 GHz)
    - ✓ 50% Xmttr (solid state)
    - ✓ 82% Rectenna
- Assessed Modularity:
  - Low @ ~2 MT per module
  - Base for 1 'Module" @ ~$50M
- Power Availability:
  - Assumed to be ~40% @ 24/7 (w/ cosine losses)
- Major In-Space Infrastructure
  - Minimal
  - SPS 100% replaced at year 15
  - Direct launch to GTO

	Baseline (15 Years)	Normalized (30 Years)
Peak Power Delivered	~100 MW	~2 GW
Transmitter Diam (km)	~3 km	~3 km
Max SPS Dimension (km)	~3 km	~3 km
SPS Mass (MT)	~700 MT (in ~350 modules)	~14,000 MT (in ~6,944 modules)
SPS HW Cost ($)	~$18 B	~ $157 B
Transport Cost ($/SPS)	~$2 B/SPS	~$3 B / SPS
Est Space Infra-structure Cost	N/A	N/A
Est. Sys. Cost (2x for 30 Yrs)	~$20 B	~ $320 B
Est. O&M Cost	~6 B 0.02% / year	~ $288 B @ 3% / year
Finance Cost	N/A	$480 B @ 5% / year
LCOE	$4.94 / kWh	~$5.20 / kWh

* *Note: No definition of attitude control; No required infrastructure; HW estimate are 'goals' only; 2021 Update*

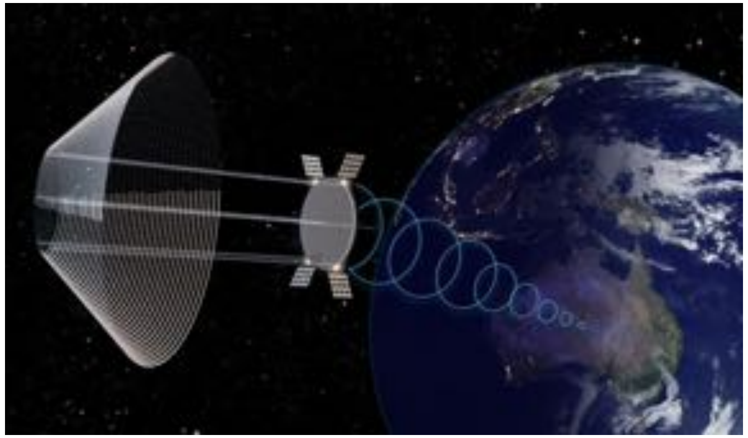
SPS-ALPHA Mk-III concept – USA | 2020
SPS Type 6 | Summary Assessment



PROS:
- Lowest mass per kWh delivered
- Lowest cost per kilowatt-hour for energy
- High modularity
- Common launchers
- No separate space infrastructure required
- Ease of ground testing / scaling up to larger SPS

CONS:
- Requires autonomous Heliostat control and operations
- Requires large structural system
- Involves Moderate technology risk in device efficiency requirements

SPS-ALPHA Mk-III concept – USA | 2020
SPS Type 6 | Details & Normalization*

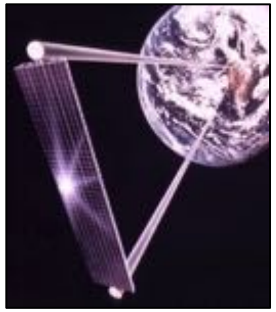
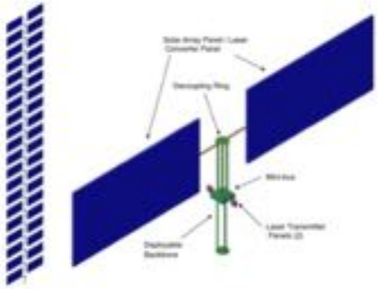
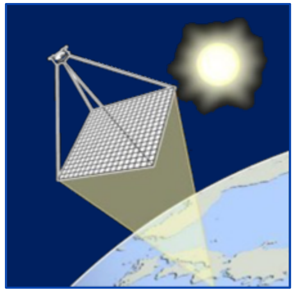
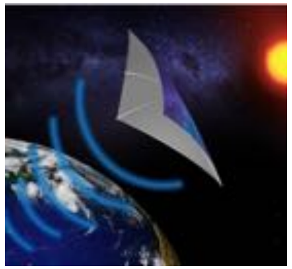


- Wavelength: 2.45 GHz
- Assumed Key Tech:
  - Robotic assessment of modular Systems
  - Independently pointed Heliostats
  - PV @ 40%
  - PMAD @ ~95%
  - WPT @ (2.45 GHz)
    - 70% Xmttr (solid state)
    - 85% Rectenna
- Assessed Modularity:
  - Very high modularity
  - ~5 kg (average) per module
- Power Availability:
  - 99.95 @ 24/7
- Major In-Space Infrastructure
  - None (incorporated into SPS hardware cost)

	Baseline
Peak Power Delivered	~2 GW
Transmitter Diam (km)	~1.7 km
Max SPS Dimension (km)	~7 km
SPS Mass (MT)	~7,500 MT
SPS HW Cost ($)	~$4 B
Transport Cost ($/SPS)	$1.5 B / SPS
Est Space Infra-structure Cost	0
Est. System Cost	~$5.5 B
Est. O&M Cost	~$5 B @ 3% / year
Finance Cost	~$8.3 B @ 5% / year
LCOE	~4-5¢/kWh

SPS Comparison

Space Solar Power Major Platform Concepts Taxonomy

Type 1	Type 2	Type 3	Type 4	Type 5	Type 6
					
EXAMPLE: 1979 Ref. SPS (US | DOE & NASA)	**EXAMPLE: Multi-Rotating Joint** (CHINA | CAST)	**EXAMPLE: Modular Electric Laser SPS** (US | AEROSPACE)	**EXAMPLE: “Simple” Integrated Sandwich SPS** (JAPAN)	**EXAMPLE: Single-Substrate Thin-Film SPS Swarm** (US | CIT-NG)	**EXAMPLE: SPS-ALPHA Mk-III** (US | MSTI)

“PLATFORM” MASS (MT)					
20,000 MT	20,000 MT	18,400 MT	18,000 MT	14,000 MT	7,500 MT
COST OF ENERGY DELIVERED ($ / KWH) OVER 30 YEAR LIFE					
$3.00 / kWh	19¢ / kWh	44¢ / kWh	72¢ / kWh	$5.20 / kWh	4-5¢ / kWh

Outline

- Introduction
- History
- Selected critical advances since the 1980s
- Comparison of Leading Approaches to Space Solar Power
- **Programmatic Activities**
- Hyper-Modular SPS-ALPHA : some detailed numbers
- Summing up

- Evolving SPS Concepts
- Launchers
  - Starship+Booster @ $100 / kg to LEO
  - Others: US (New Glenn), NZ (Rocket Lab), China, Japan (Honda, JAXA), UK (Reaction Engines Ltd.), ESA
- Evolving Market Context for SSP
  - Carbon Net-Zero Policy Goals
  - Isolated Commercial Ops (e.g., Mining) transition to EVs
  - Cis-Lunar / Lunar Surface Operations
  - CitiGroup Commercial Space Rept (SSP @ $23B sales by 2040)
- R&D and Studies
  - AFRL SSP R&D “SPIDR” for military applications
  - CalTech SSP Technology Research
  - CAST & China : new labs, new national committee
  - UK Assessment of SSP – Creation of Space Power Initiative
  - Academic Studies (ISU, RMIT)
  - New Japanese SSP Objective
  - ESA Cost-Benefit Assessment (2021-2022 @ ~$400K±
  - NASA Cost-Benefit Study (just started)
  - IAA Permanent Committee on SSP (Workshop in September)

Recent & Relevant...

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Hyper-Modular Architectural Approach

Complex, "hyper-modular" architectures found in Nature…

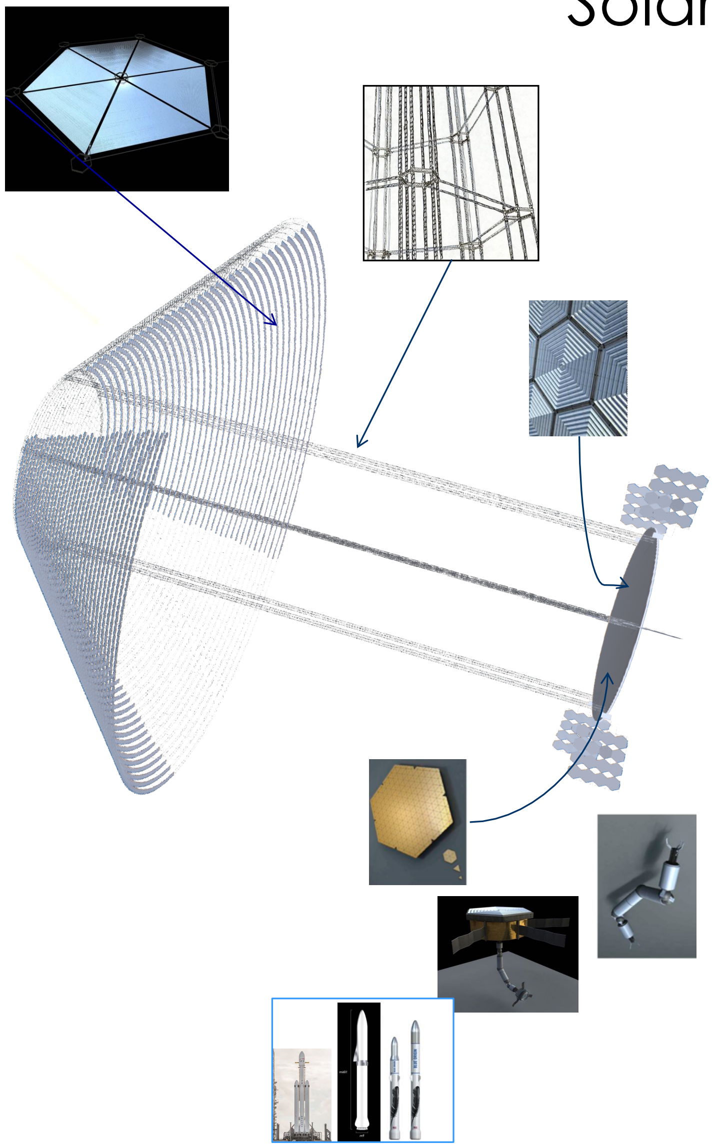
Single genetic "individuals" comprising thousands to tens of thousands of "modules"

- Example: Ants – capable of forming structural systems from themselves
- Example: Bees – capable of navigation, cooperation and construction

Diverse genetic "individuals" in a single community comprising 100s of species and many 1000's of individuals

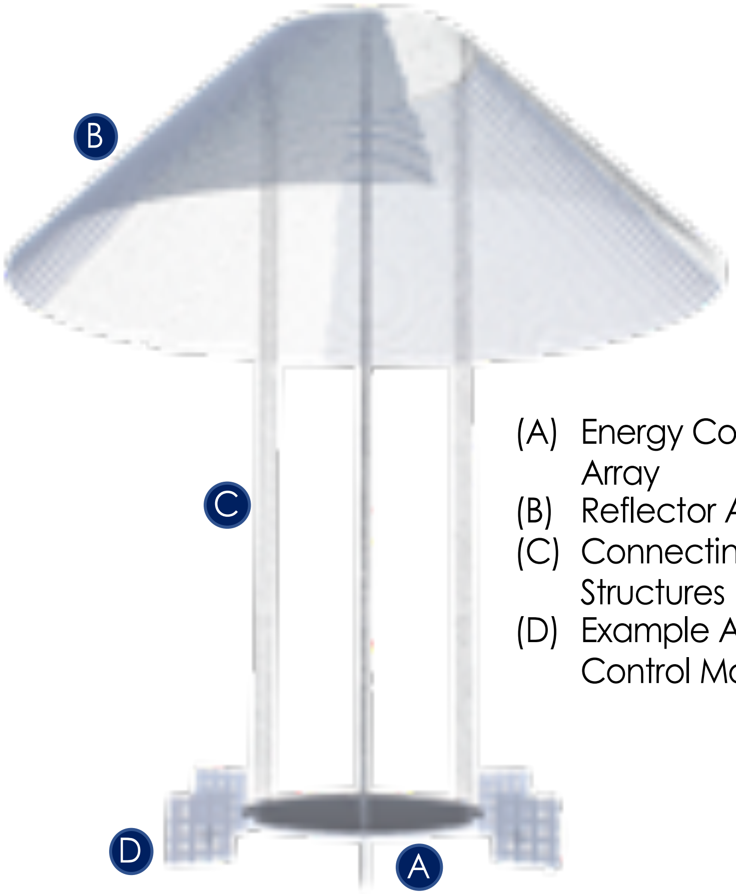
- Example: coral reefs, composed of coral (living and skeletons of dead), fungi, algae, sponges, fish, worms, etc., etc.

Solar Power Satellite via Arbitrarily Large Phased Array
SPS-ALPHA

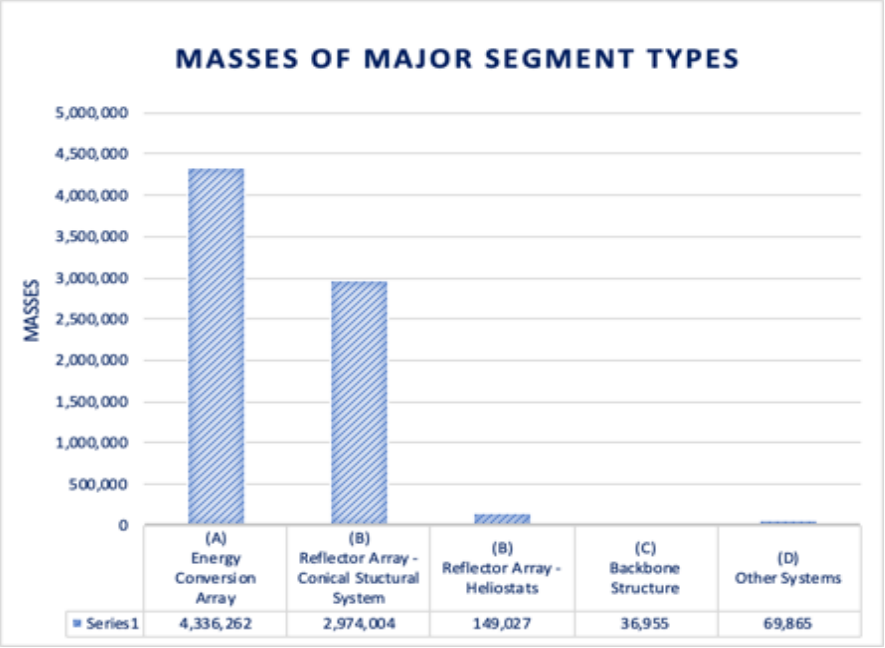


- SPS-ALPHA represents a novel physical / optical configuration that enables energy distribution by photons and local waste heat rejection...
- SPS-ALPHA intelligent modular elements include the following:
  - “Cubesat” sized modular interconnections
  - Deployable structural modules
  - Local solar power generation, management and distribution and thermal
  - RF payload modules
  - Deployable large thin-film reflectors
  - Mass-produced modular robots providing all manipulation
  - Stand-alone propulsion and attitude control modules

SPS-ALPHA Highlights



- (A) Energy Conversion Array
- (B) Reflector Array
- (C) Connecting Boom Structures
- (D) Example Attitude Control Modules



	BASELINE
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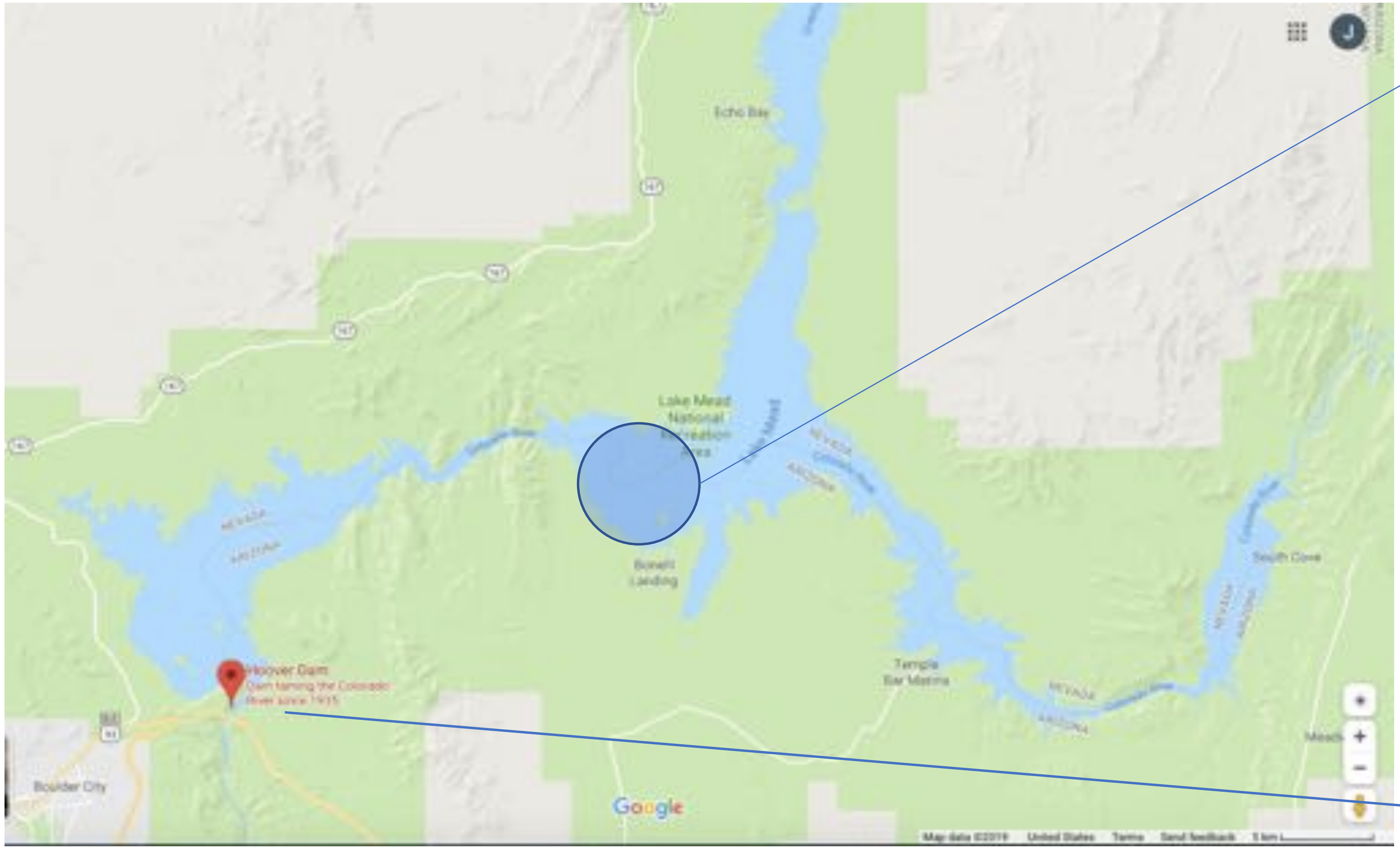
TRANSMITTER DIAM (KM)	~1.7 km
MAX SPS DIMENSION (KM)	~7 km
SPS MASS (MT)	~7,500 MT
SPS HW COST ($)	~$4 B
TRANSPORT COST ($/SPS)	$1.5 B / SPS
EST SPACE INFRA-STRUCTURE COST	0
EST. SYSTEM COST	~$5.5 B
EST. O&M COST	~$5 B @ 3% / year
FINANCE COST	~$8.3 B @ 5% / year
LCOE	~4-5¢/kWh

Comparison: SPS-ALPHA / Receiver vs Hoover Dam



SPS-ALPHA Receiver

Area: 1.0-to-1.5 x ~27 km^2

Capacity: ~2.1 GW

Annual Energy: ~18,000 GW-hours

Hoover Dam

Catchment Area: ~435,000 km^2

Reservoir Area: ~640 km^2

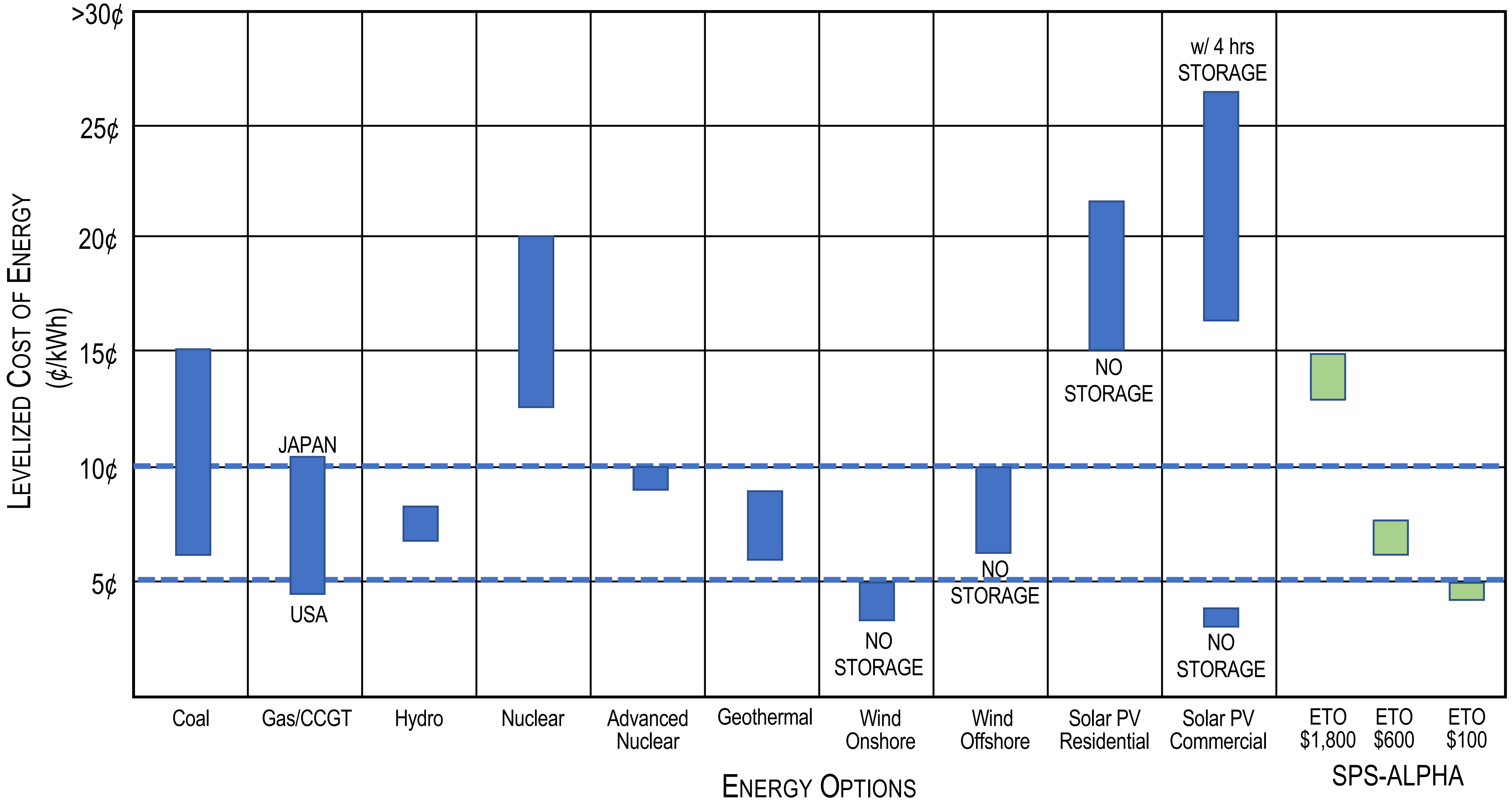
Capacity: ~0.5 GW (Ave; 2 GW peak)

Annual Energy: ~4,000 GW-hours

Dam Investment: ~$ 50M c. 1931

Ref: https://en.wikipedia.org/wiki/Hoover_Dam (19 Jan '22)

Comparison of Energy Source Options (Lazard's 2021 – Plus IEA, etc.)



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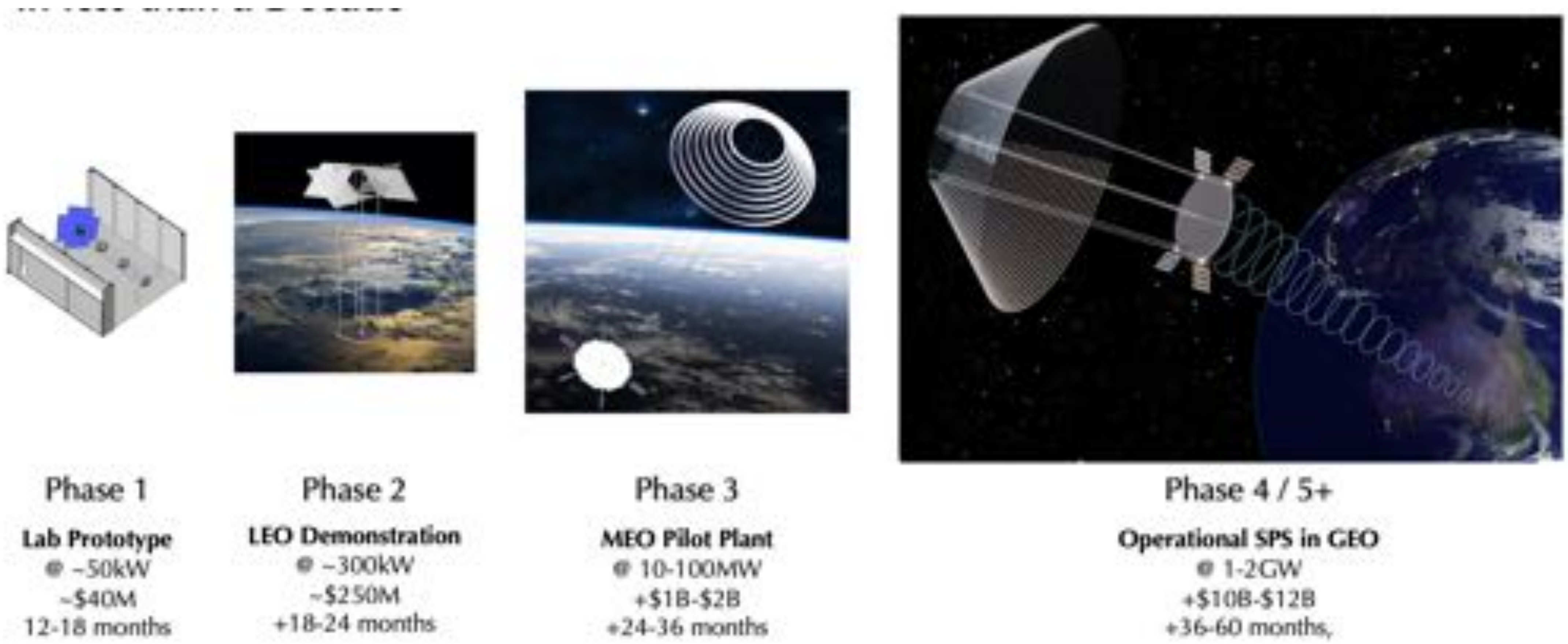
A Practical Near-Term Roadmap to SPS

Opportunity for the US to

- Lead the International Community
- Establish "rules of the road" for commercial Space Solar Power



Potential "First System"