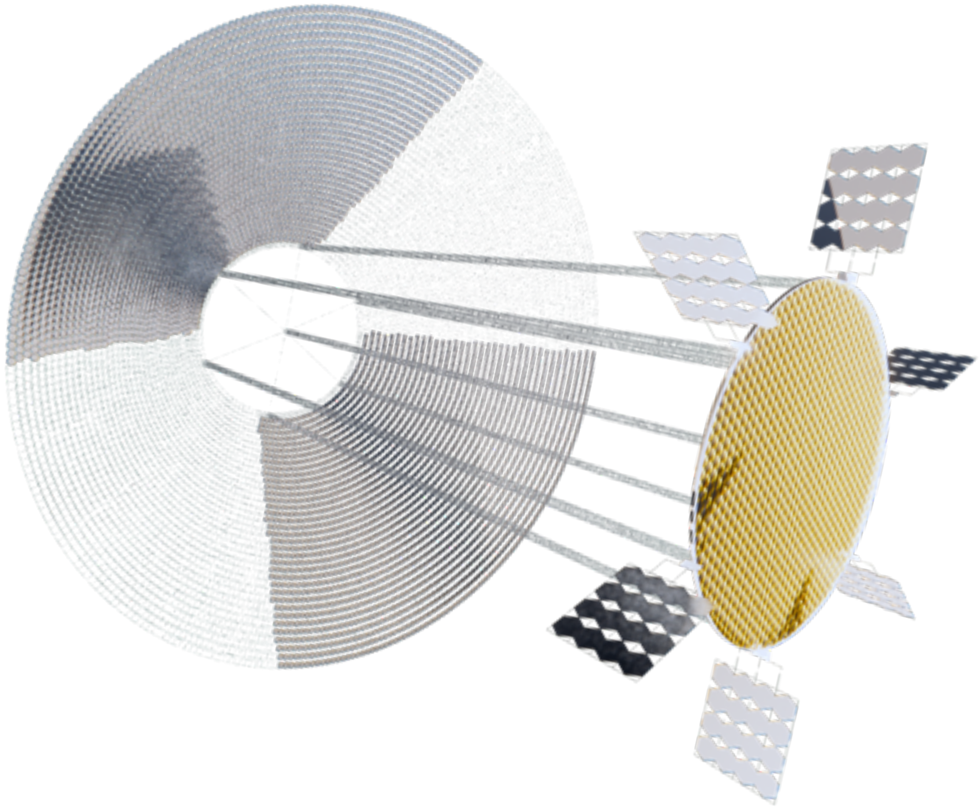


Space Solar Power: An Overview

28 May 2022

John C. Mankins
john.c.mankins@artemisinnovation.com
Chair, IAF Power Committee
Chair, IAA Space Solar Power Permanent Committee
Director, Solar Space Technologies LTD, Pty.
President, Artemis Innovation Management Solutions LLC
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

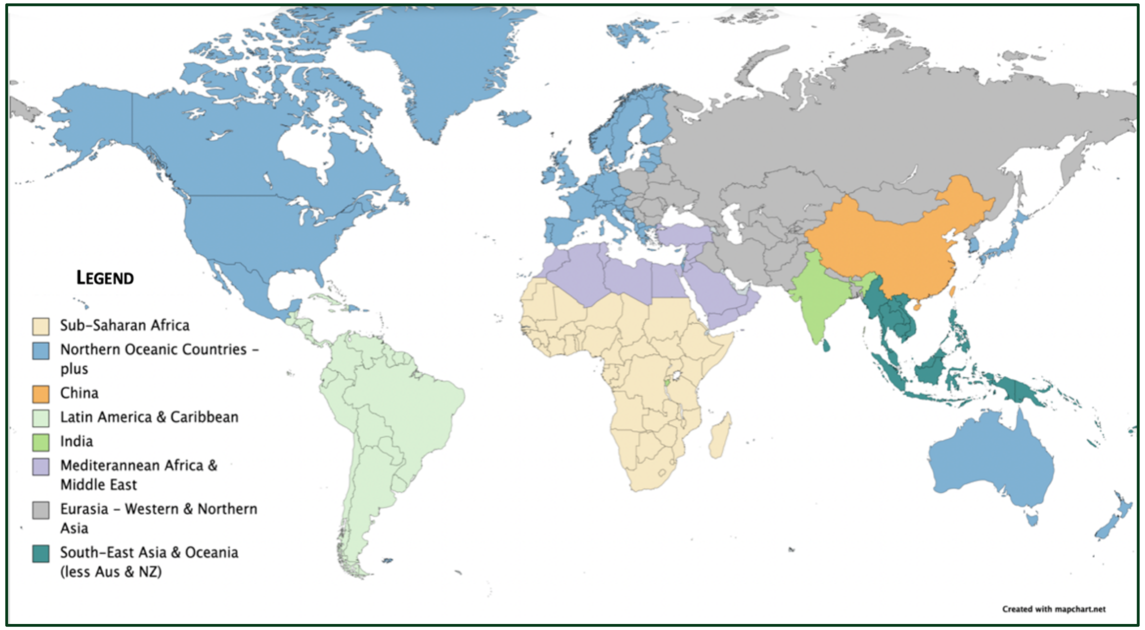
Provide Sustainable Energy to an additional ~6 Billion in "emerging economies" during this Century

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



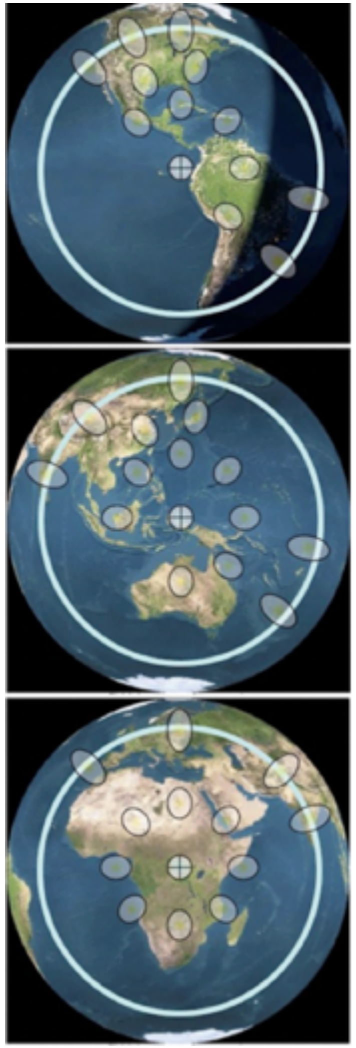
INDIA
Population Today: 1.45 Billion
Energy Today : **7,800-kWh** per person
Population in 2100: 1.45 Billion

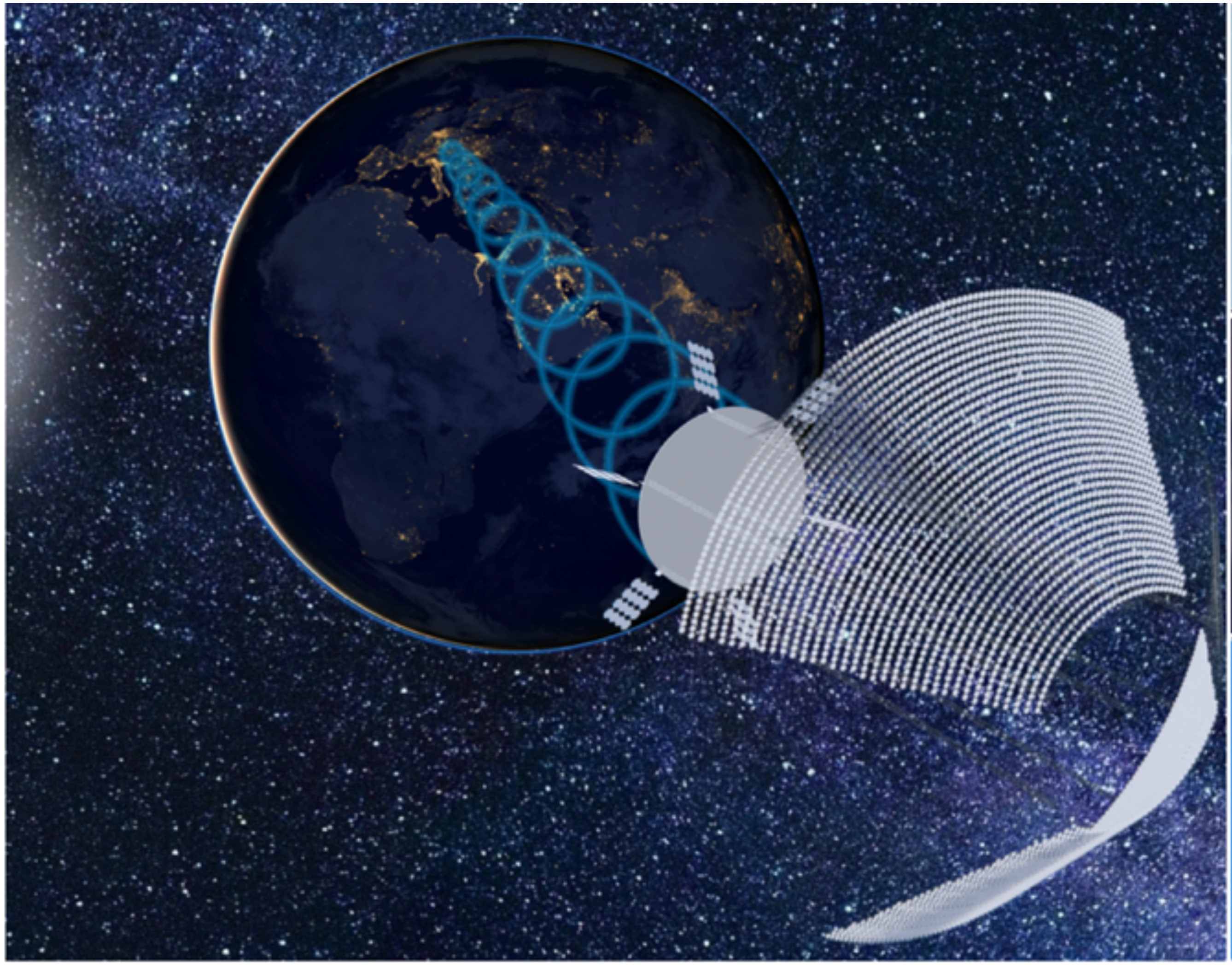
SOUTH-ASIA & OCEANIA
Population Today: 0.71 Billion
Energy Today : **14,600-kWh** per person
Population in 2100: 0.79 Billion

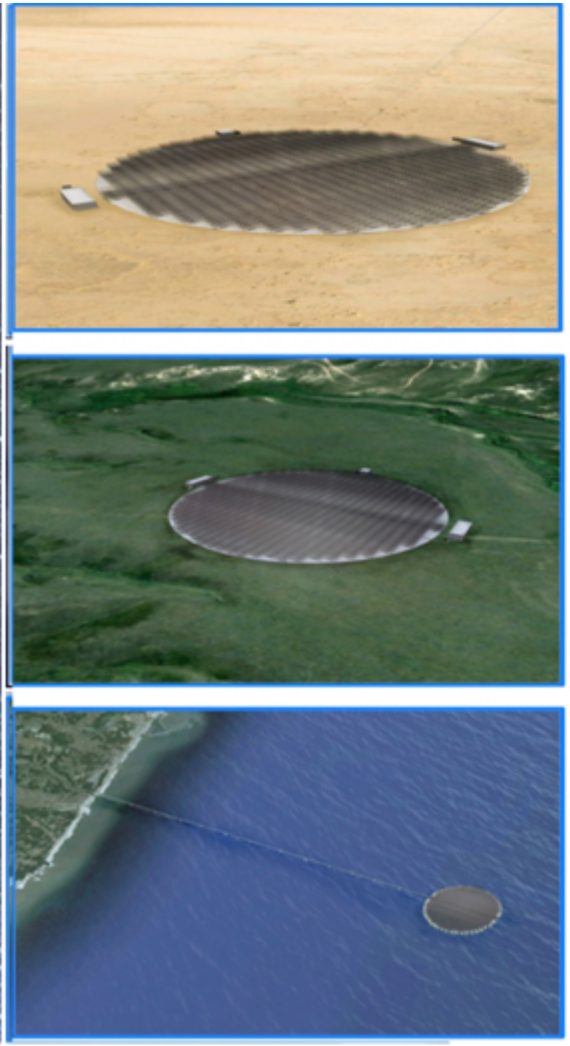
SUB-SAHARAN AFRICA
Population Today: 1.09 Billion
Energy Today : **5,900-kWh/**person
Population in 2100: 3.7 Billion

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



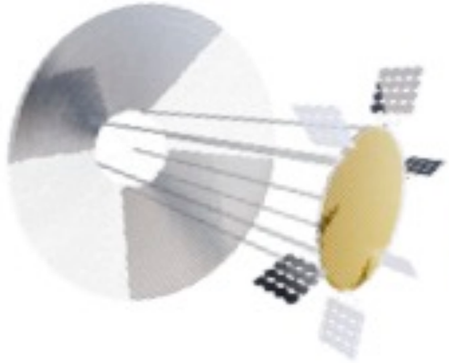




How Would Space Solar Power Work?

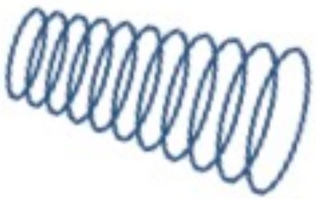
THE SUN

- 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

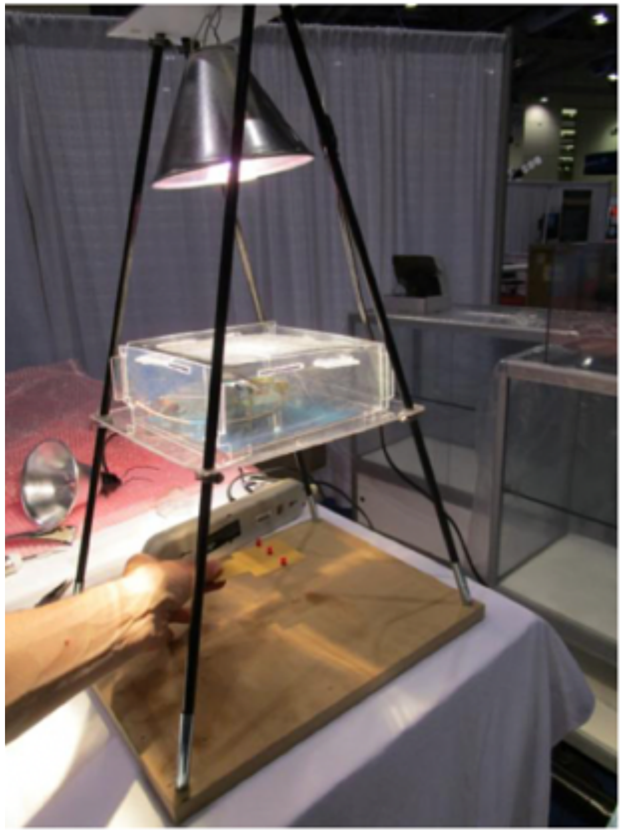
EXISTING INFRASTRUCTURE

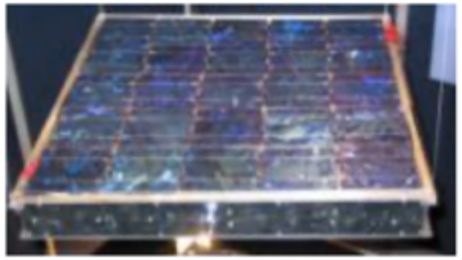
- DC or AC fed into the local grid
- Resembles Hydroelectric Power – but…
- “Always” available
- “Shareable” across markets

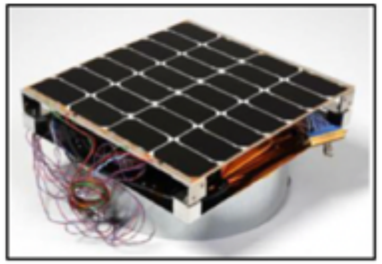
HOMES AND BUSINESSES

- 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



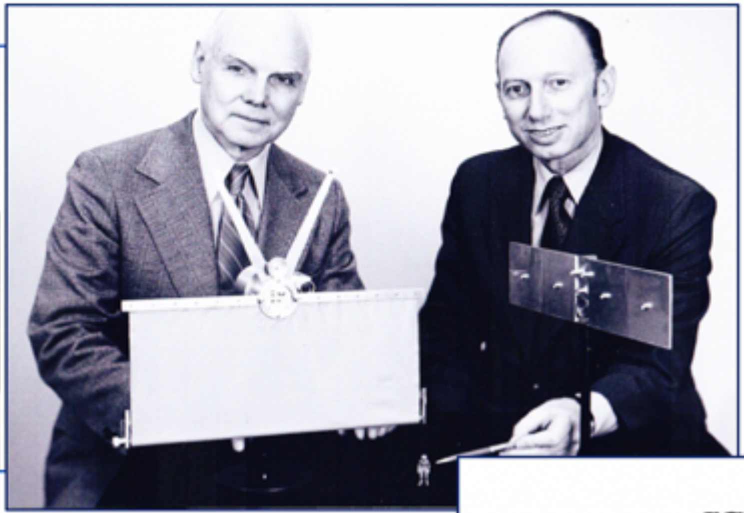




Outline

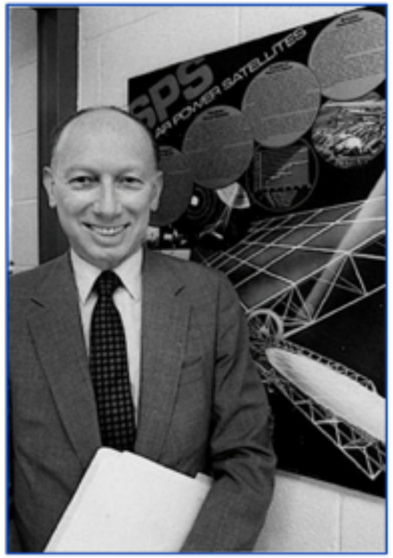
- Introduction
- **History**
- Selected critical advances since the 1980s
- Comparison of Leading Approaches to Space Solar Power
- Programmatic Activities
- Hyper-Modular SPS-ALPHA : some detailed numbers
- Summing up

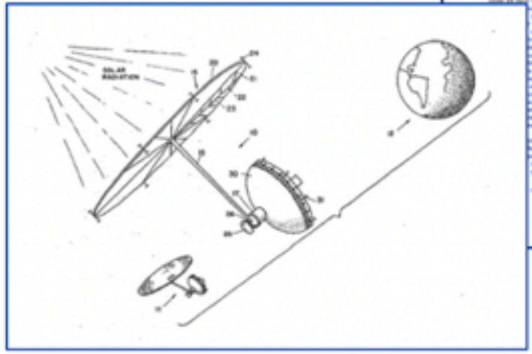
1940s-1960s



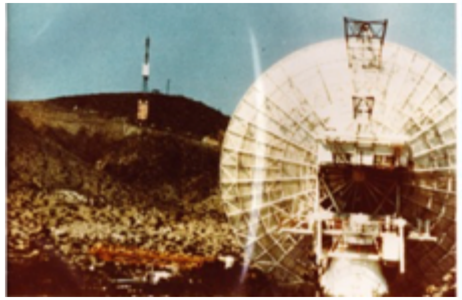

SCIENCE

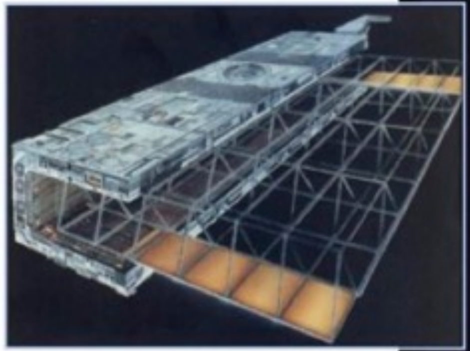
Power from the Sun: Its Future

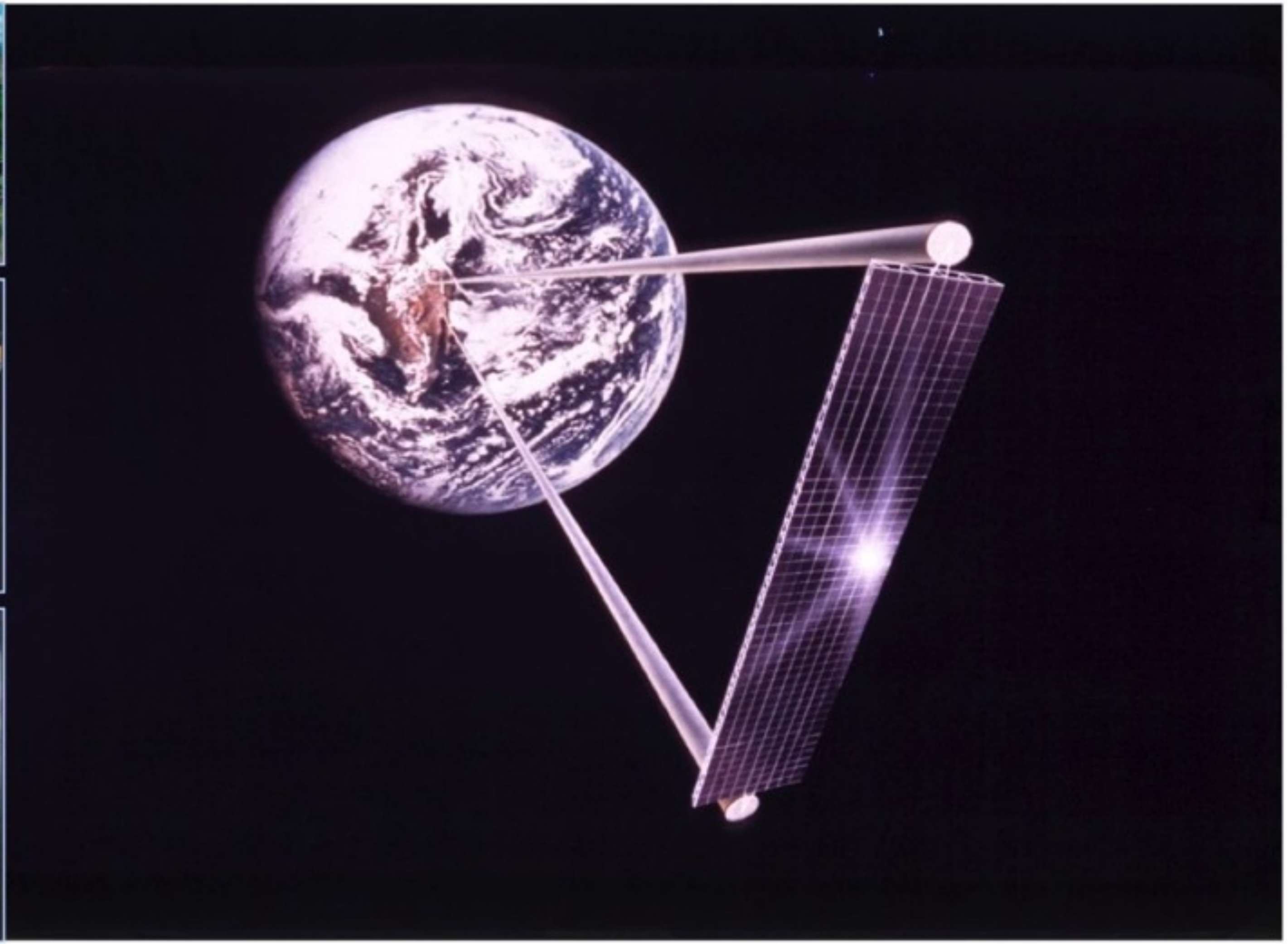




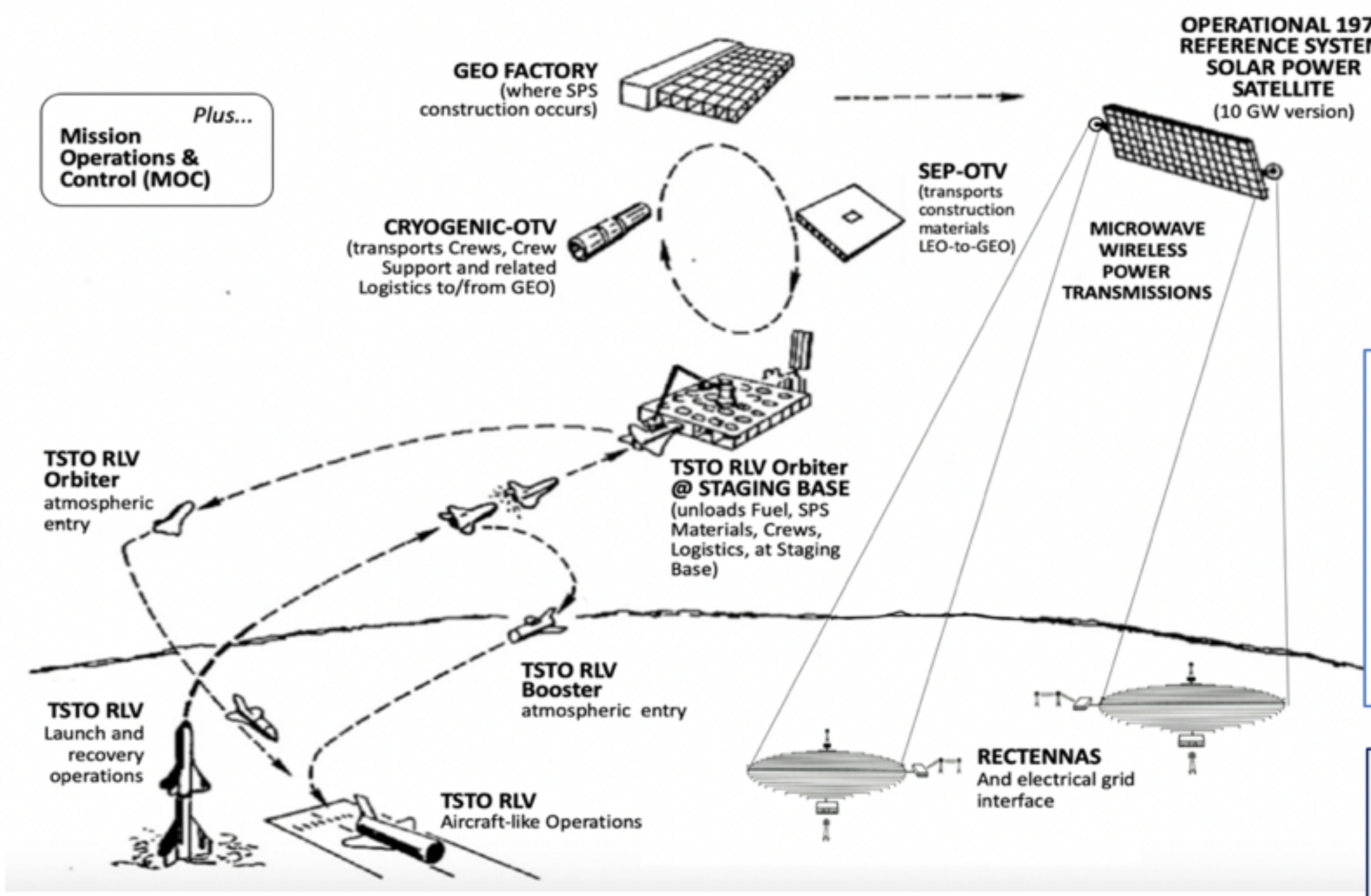
1970s-1980s

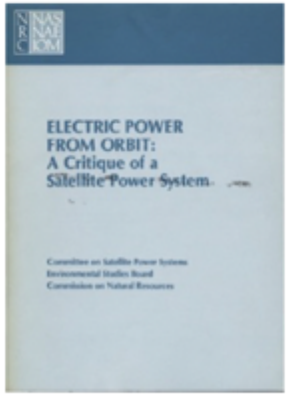


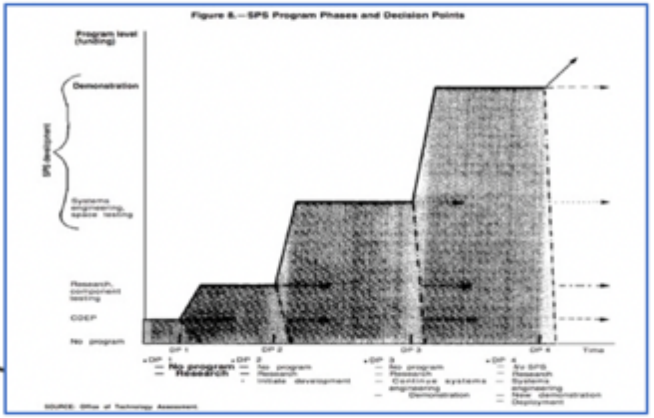




1979 Reference System - CONOPS

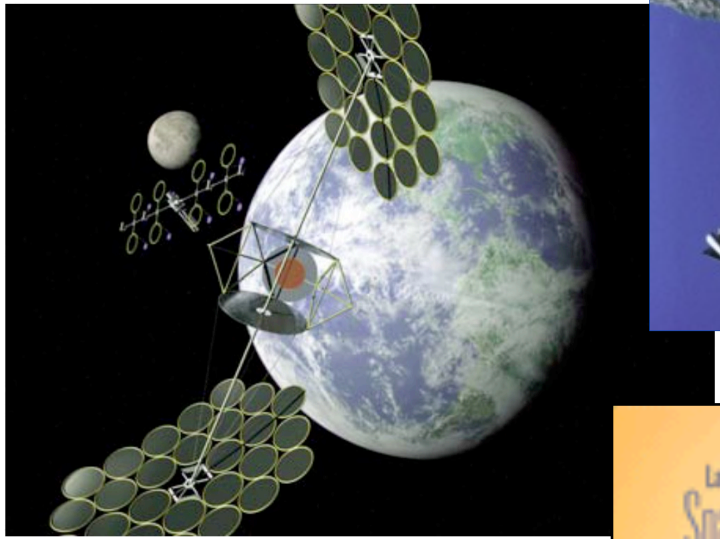


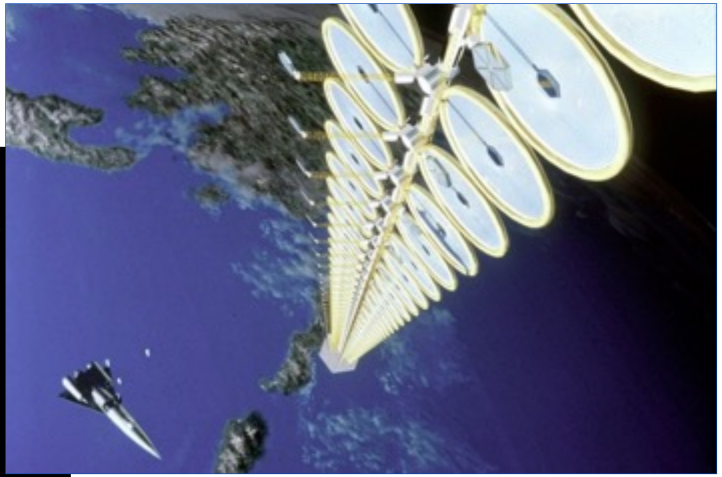


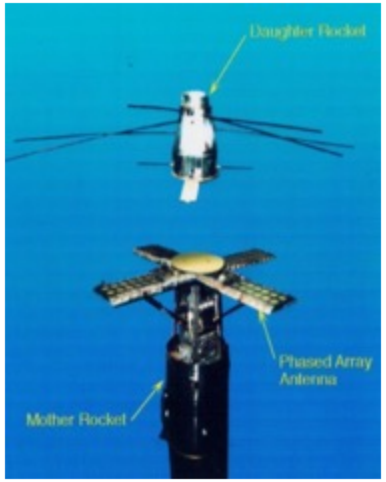


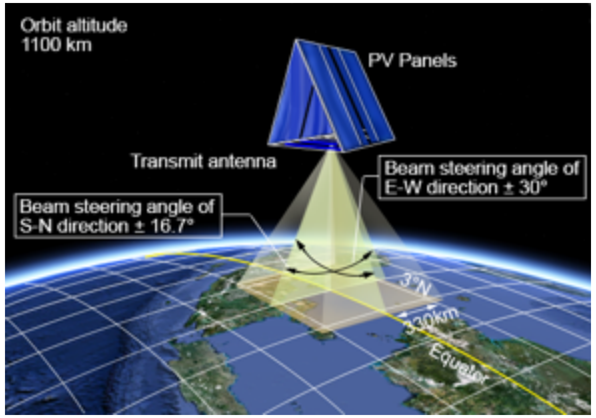
Using 1976 Technology
Roughly 20 years &
$1,000 B to "First kW-hr"

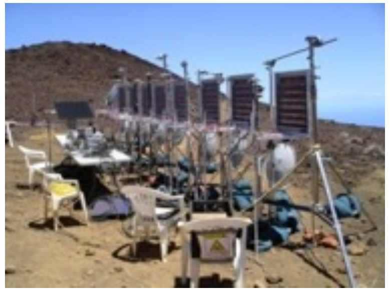
c. 1990 to c. 2015

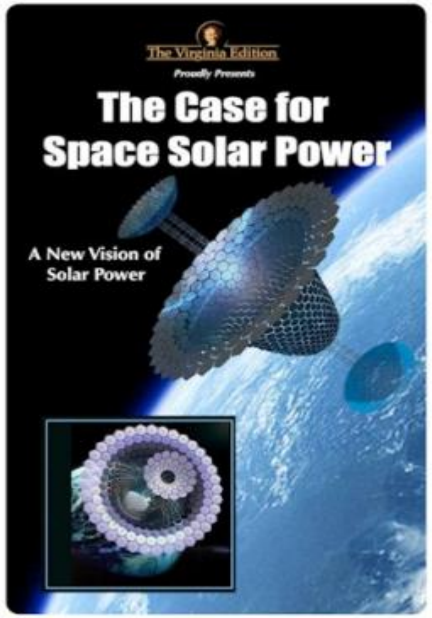












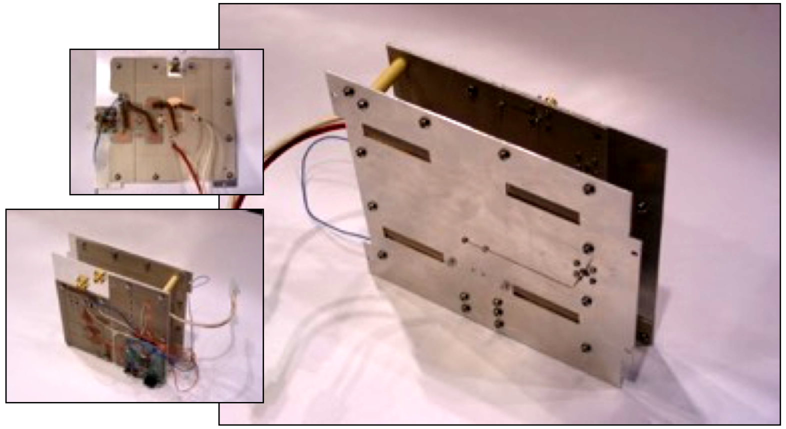
Outline

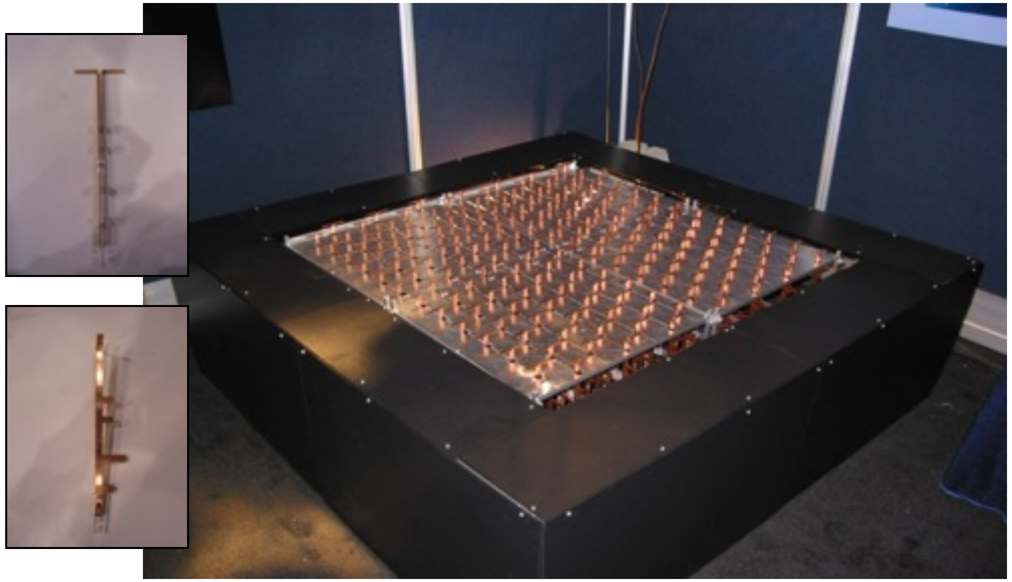
- Introduction
- History
- **Selected critical advances since the 1980s**
- Comparison of Leading Approaches to Space Solar Power
- Programmatic Activities
- Hyper-Modular SPS-ALPHA : some detailed numbers
- Summing up

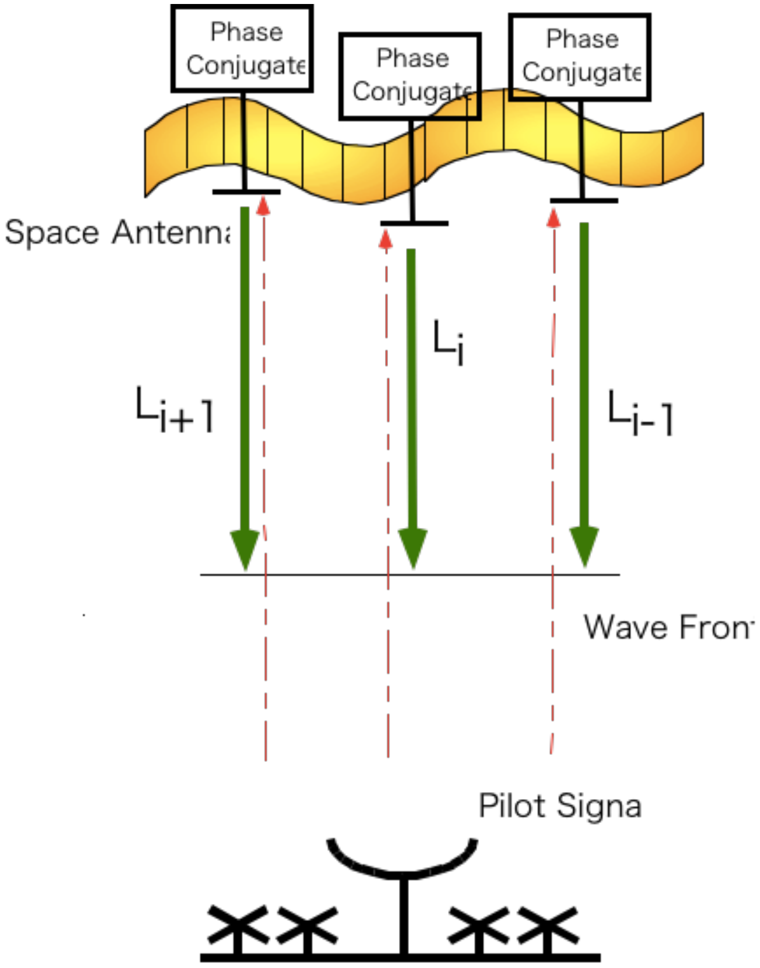
Since 1980, multiple revolutionary advances...

- 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

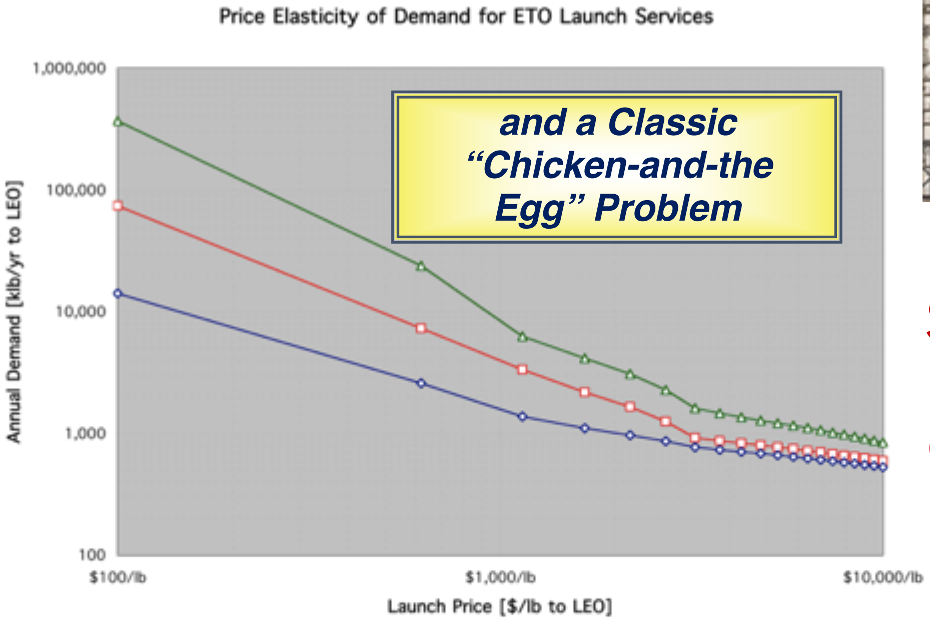






Realizing Low Cost Space Launch

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



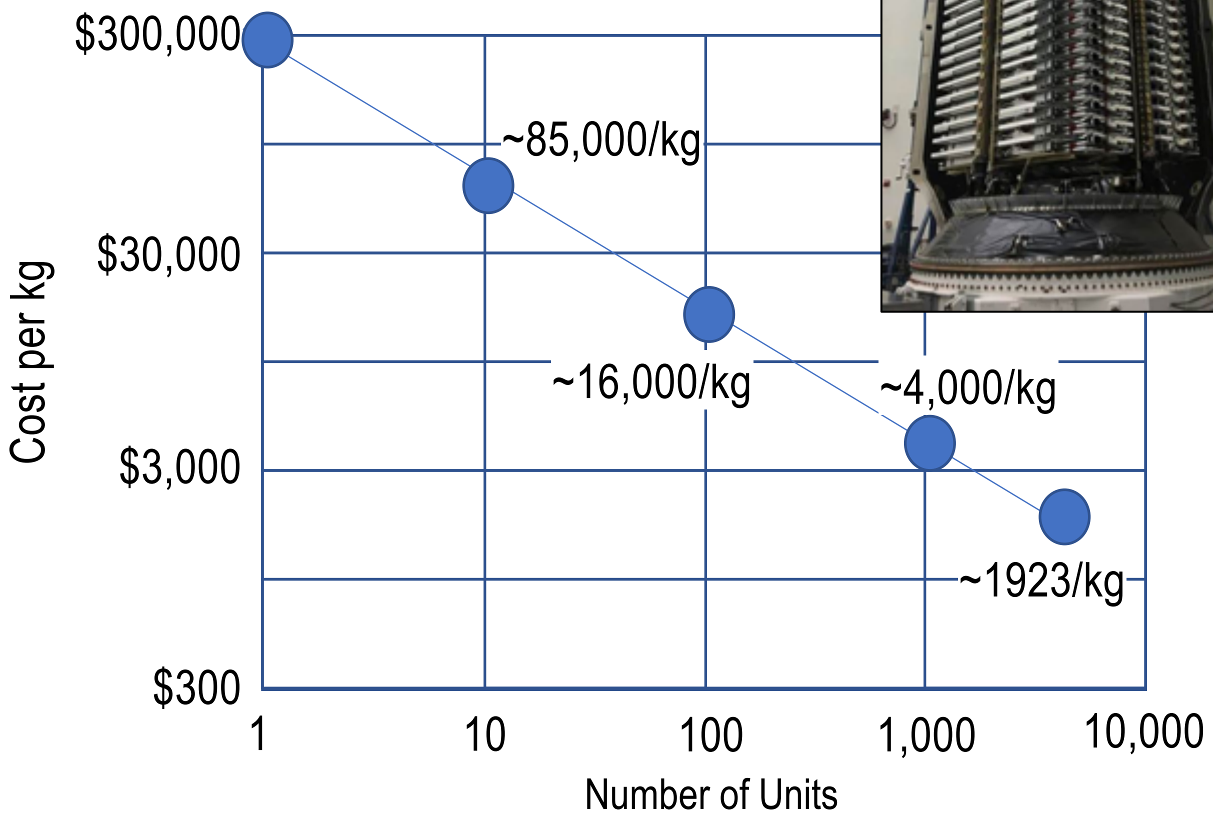
Present
Since 2015...
LEO Launch Cost
@ < $2,000/kg
Reduction >90%

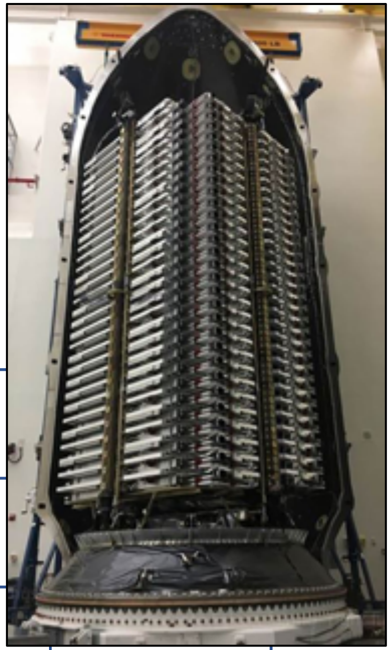
Future
After ~2025 (?)...
LEO Launch Cost
@ ~ $100/kg to LEO
Reduction: >99%

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%





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

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

27 MAY UPDATE DRAFT

- 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?
  - Special Question: Lunar Surface ?

SPS Taxonomy (1 of 2)

27 MAY UPDATE DRAFT

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)

Type 7
Lunar Surface Based
No Moving Parts
Passive Thermal
Modular
Robotic Assembly
GEO-Based Reflector Only
All lunar materials
Requires extensive lunar development
(PV, Structures, Electronics, etc.)

Lunar Solar Power
(US | CRISWELL)
LUNA RING
(JAPAN | SHIMIZU)

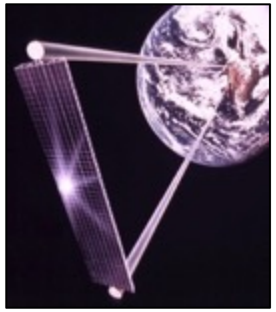
Special Technical Challenges

SPS Taxonomy (1 of 2)

27 MAY UPDATE DRAFT

Space Solar Power Major Platform Concepts Taxonomy

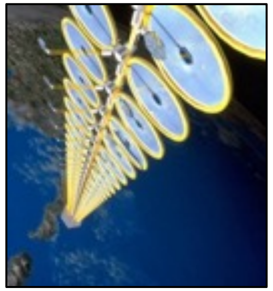
Type 1



1979 Ref. SPS
(US | DOE & NASA)

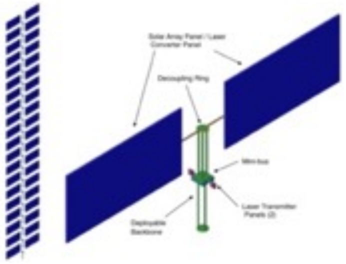
Special Technical Challenges

Type 2



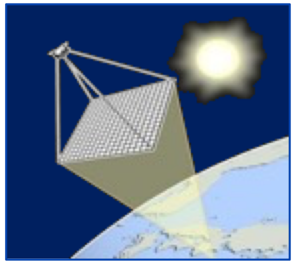
Multi-Rotating Joint
(CHINA | CAST)
Sun Tower / Sail Tower
(US | NASA)
Multiple Array Central Transmitter
KOREA / KARI

Type 3



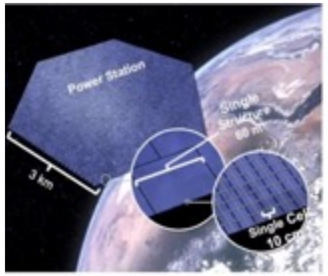
Modular Electric Laser SPS
(US | AEROSPACE)

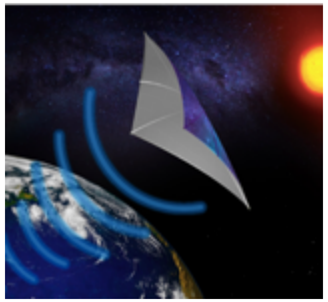
Type 4



"Simple" Integrated Sandwich Module SPS
(JAPAN)

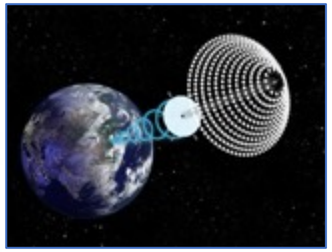
Type 5

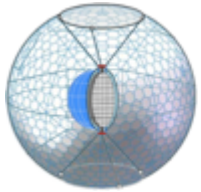




Single-Substrate Thin-Film SPS Swarm
(US | CIT-NG)

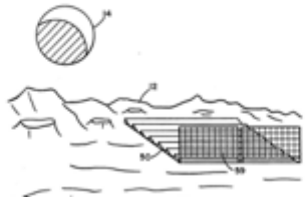
Type 6

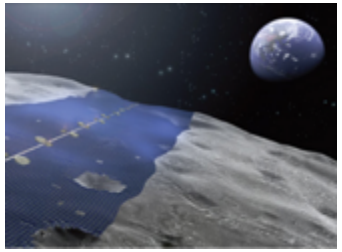




SPS-ALPHA
(US | MSTI)
Cassiopeia
(UK | CASH)
SPS-OMEGA
(CHINA | CASH)

Type 7





Lunar Solar Power
(US | CRISWELL)
LUNA RING
(JAPAN | SHIMIZU)

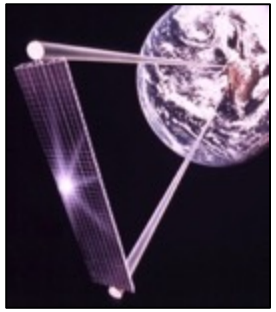
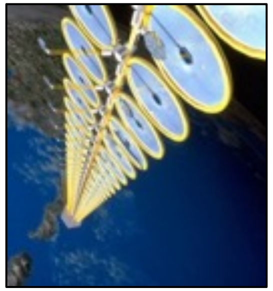
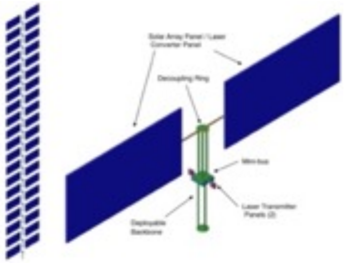
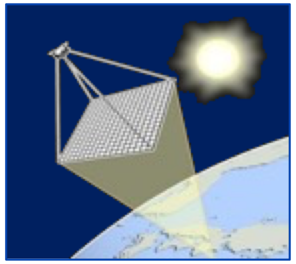
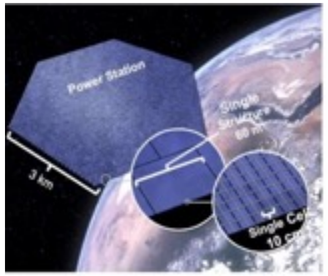
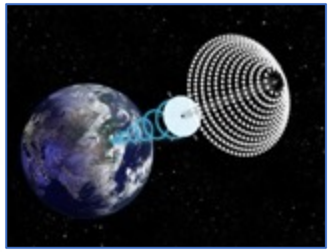
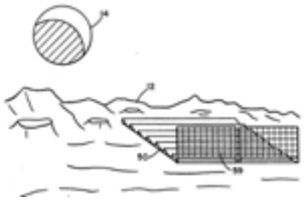
Comparison of SPS Options: Common **Assumptions**

- 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 & 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
- Operations in GEO (35,000 km distance for power transmission)
    - With Lunar Surface WPT + GEO Reflector as a special Case

SPS Comparison

Space Solar Power Major Platform Concepts Taxonomy

27 MAY UPDATE DRAFT

Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7
						
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)	**EXAMPLE: LSP** (US | CRISWELL)

"PLATFORM" MASS (MT)						
20,000 MT	20,000 MT	18,400 MT	18,000 MT	14,000 MT	7,500 MT	?? 2,000 GT ??
COST OF ENERGY DELIVERED ($ / KWH) OVER 30 YEAR LIFE						
$3.00 / kWh	19¢ / kWh	44¢ / kWh	72¢ / kWh	$5.20 / kWh	4-5¢ / kWh	?? $100/ kWh ??

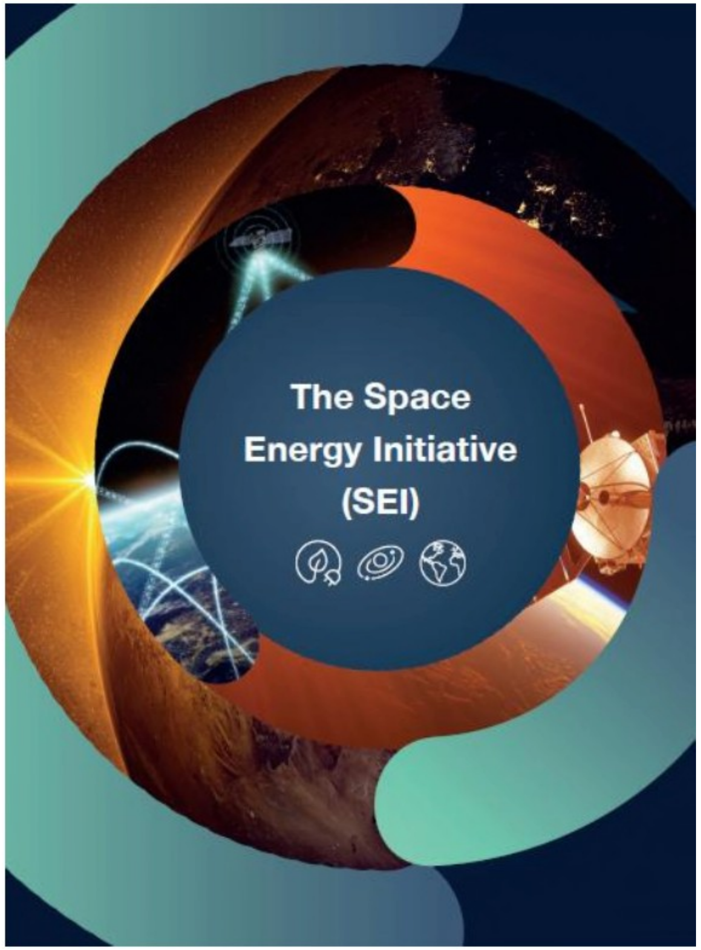
Outline

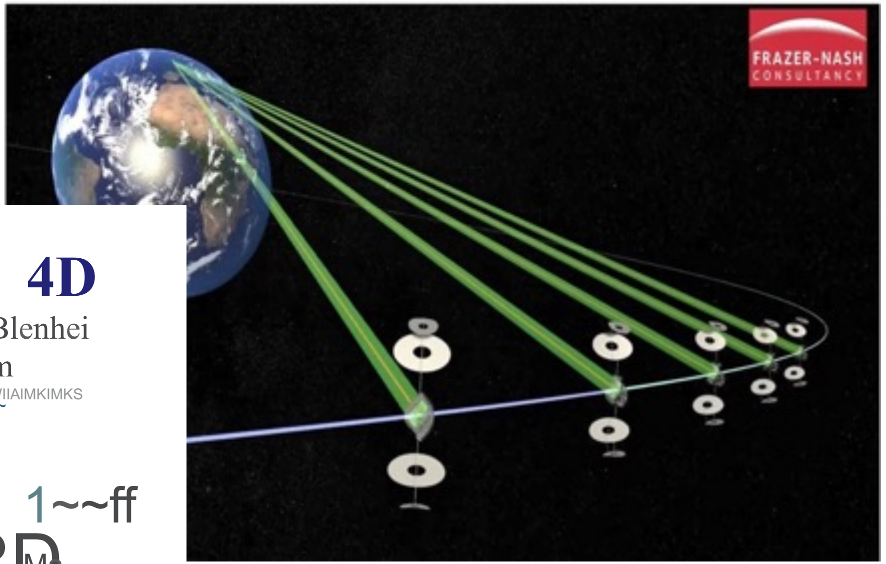
- Introduction
- History
- Selected critical advances since the 1980s
- Comparison of Leading Approaches to Space Solar Power
- **Programmatic Activities**
- Hyper-Modular SPS-ALPHA : some detailed numbers
- Summing up

Recent & Relevant...

- Launchers
  - Starship+Booster, New Glenn, Rocket Lab, China, JAXA, ESA
- Evolving SPS Concepts
- Evolving Market Context for SSP
  - Carbon Net-Zero Policy Goals
  - Cis-Lunar / Lunar Surface Operations
  - Remote Commercial Operations
- 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)**
  - Newly-formed IAA Permanent Committee on Space Solar Power (Workshop in September)
  - CitiGroup Assessment of Commercial Space to 2040

UK – Space Energy Initiative





Objective:
SPS for Carbon Net Zero by 2050

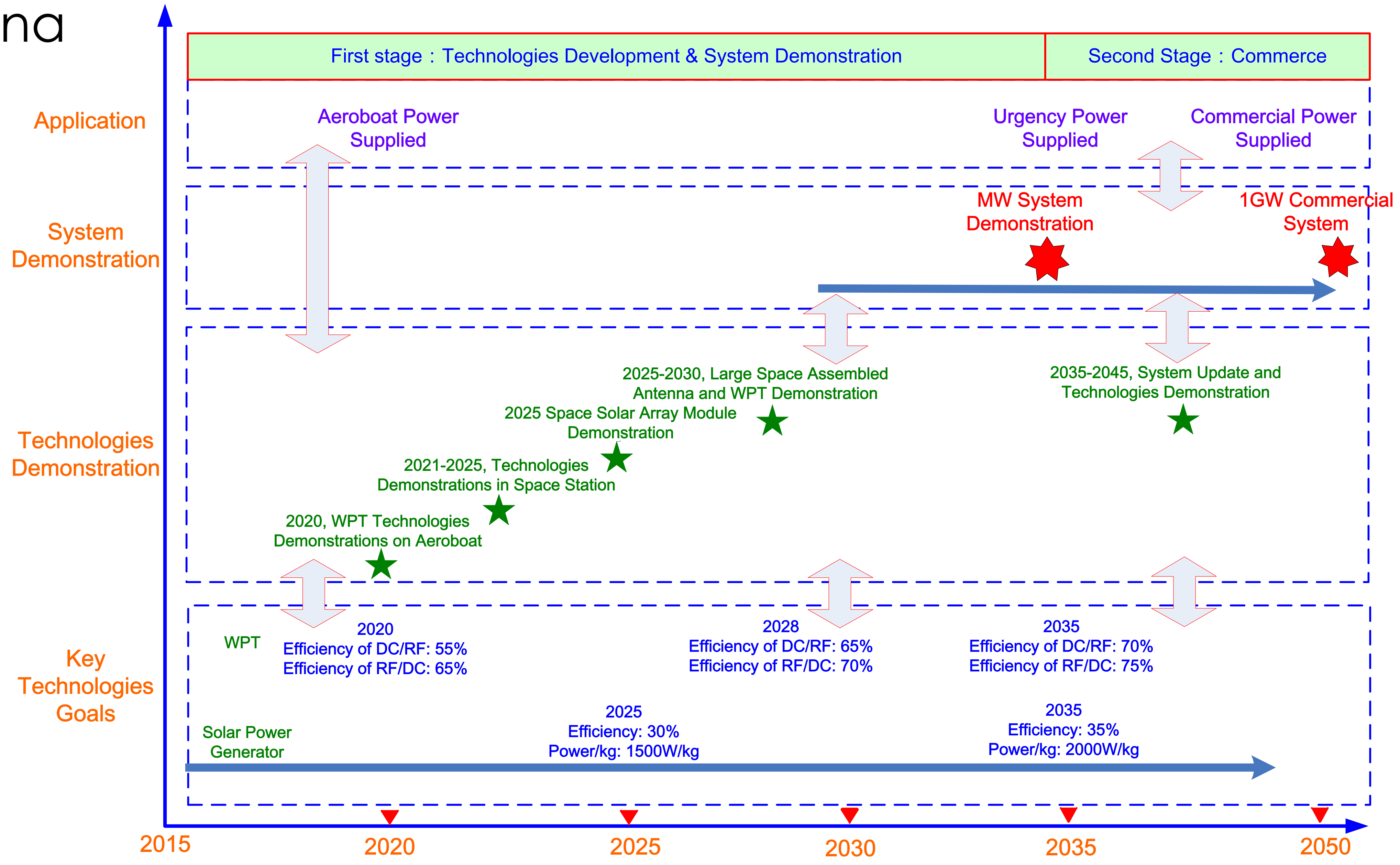
SSP in China
(1 of 3)

Recent SPS activities in China

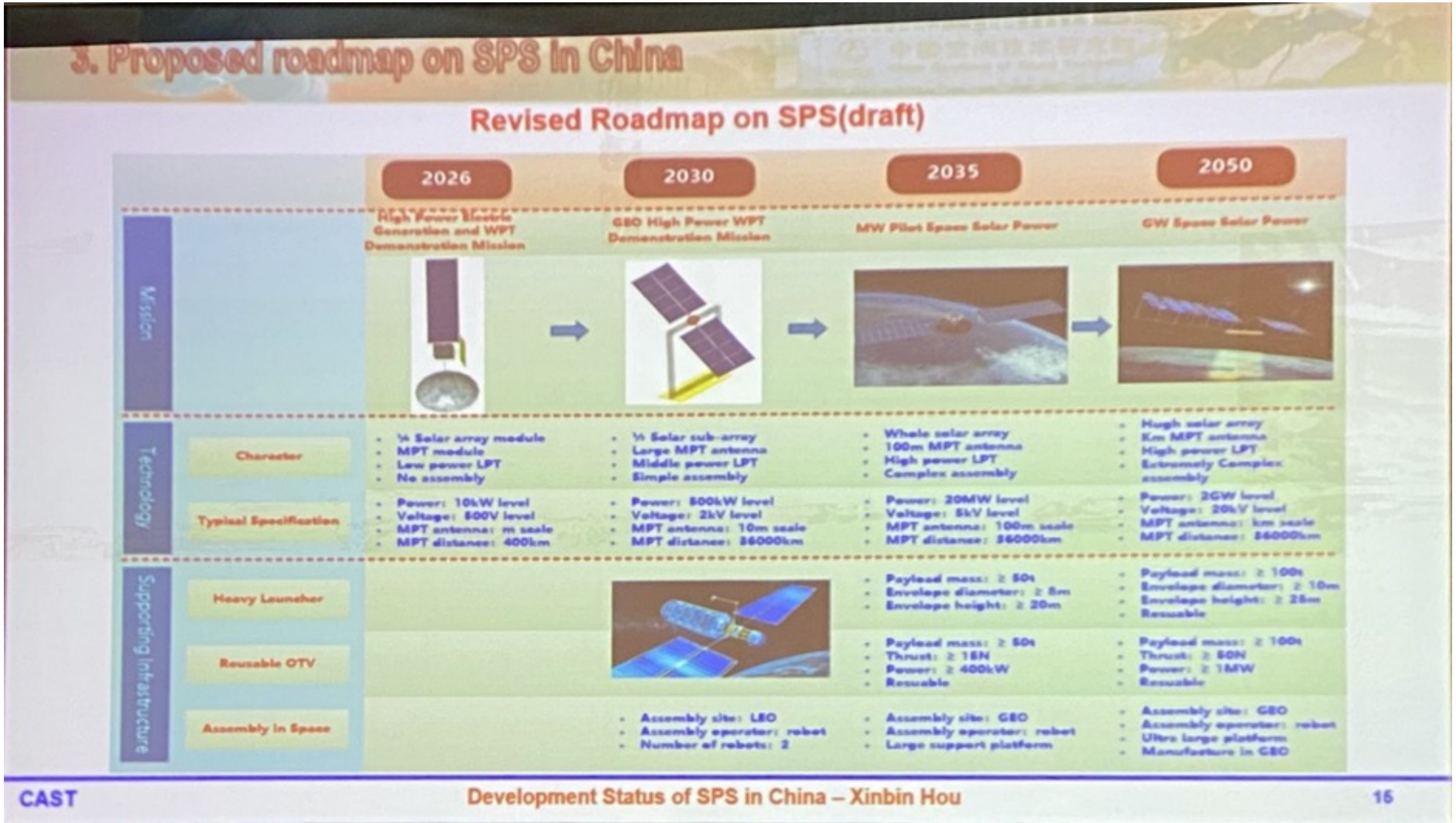
- **A Space Solar Power Experiment Base is being set up in ChongQing and the project was announced on December 6, 2018.**

- **The ZhuRi (Chase the Sun) Project was started on December 23, 2018 and a SPS demonstration base will be founded in Xi’an.**

SSP in China
(2 of 3)



SSP in China
(3 of 3)



Objectives:

10 kW by 2026

500 kW by 2030

20 MW by 2035...

Japan 'basic space law' SSP objective (December 2021)

宇宙基本計画工程表（令和3年度改訂）のポイント

令和３年１２月２８日
内閣府
宇宙開発戦略推進事務局

＜最近の情勢＞	＜工程表改訂のポイント＞
１．宇宙安全保障の確保	
・安全保障における宇宙の役割が拡大 ・米国では、極超音速滑空弾（HGV）等への対応策として小型衛星コンステレーション構築の動きが加速	・ミサイル防衛等のための衛星コンステレーションについて、特に極超音速滑空弾（HGV）探知・追尾の実証に係る調査研究を行う。 ・宇宙作戦群（仮称）を新編（自衛隊）し、2023年度から宇宙状況把握システムの実運用を行うとともに、宇宙状況監視衛星を2026年度までに打上げるなど、国として宇宙状況監視の体制強化を進める。 ・準天頂衛星システム、情報収集衛星、通信衛星等の宇宙システムを着実に整備する。
２．災害対策・国土強靭化や地球規模課題の解決への貢献	
・災害対策・国土強靭化が喫緊の課題となる中、衛星による貢献の可能性 ・2050年カーボンニュートラル達成に向けた宇宙からの貢献への期待	・高頻度観測が可能な我が国独自の小型のレーダー（SAR）衛星コンステレーションを2025年度までに構築すべく、関係府省による利用実証を行い、国内事業者による衛星配備を加速。 ・宇宙太陽光発電の実現に向けて、各省が連携して取組を推進。マイクロ波方式の宇宙太陽光発電技術について、2025年度を目途に地球低軌道から地上へのエネルギー伝送の実証を目指す。 ・衛星等を活用した国際的な温室効果ガス観測ミッション構想を策定・推進し、世界各国によるパリ協定に基づいた気候変動対策による削減効果の確認に活用されることを目指す。
３．宇宙科学・探査による新たな知の創造	
・欧米や中国等の火星探査計画が活発化 ・アルテミス計画について、着実に取組を進める必要	・アルテミス計画による月面探査等について、ゲートウェイの機器開発や、移動手段（有人与圧ローバ）の開発研究など、月面活動に必須のシステムの構築に民間と協働して取り組む。また、米国人以外で初となることを目指し、2020年代後半を目途に日本人による月面着陸の実現を図る。 ・2029年度の人類初の火星圏からのサンプルリターン実現に向け、2024年度に火星衛星探査計画（MMX）の探査機を確実に打ち上げる。
４．宇宙を推進力とする経済成長とイノベーションの実現	
・デジタルトランスフォーメーションを支えるインフラとしての役割が拡大 ・新たな宇宙活動のための制度環境整備の必要性	・衛星データの利用拡大に向けて、自治体等とも連携し、地域の課題解決につながるデータ利用ソリューションの集中的な開発・実証を推進する。 ・米国との連携なども視野に入れながら、宇宙港の整備などによるアジアにおける宇宙ビジネスの中核拠点化を目指して、必要な制度環境を整備する。 ・2021年度内に軌道利用のルール全般に関する中長期的な方針を策定し、軌道利用に関する国際的な規範形成に向けて取り組む。
５．産業・科学技術基盤を始めとする我が国の宇宙活動を支える総合的基盤の強化	
・海外で小型衛星コンステレーションの活用拡大に向けた取組が加速 ・光通信等の次世代の宇宙技術が、民生・安保の分野を問わず必要不可欠となり、経済安全保障上も、ますます重要に	・次世代の小型衛星コンステレーションの重要基盤技術である低軌道衛星間光通信、軌道上自律制御技術等について、できる限り早期に実証衛星を打ち上げることを念頭に、我が国が先行して獲得するための取組を行う。 ・将来宇宙輸送システムについて、抜本的な低コスト化等の実現に向けて、国際的な市場動向を踏まえつつ、官民共創で研究開発を推進。 ・日米豪印の４か国で気候変動リスクや海洋・海洋資源の持続可能な利用等に関する衛星データの交換や、インド太平洋地域の国々への能力構築支援、国際的ルールづくり等についての議論を進めていく。 ・人工衛星の開発等宇宙活動に参画する機会を提供する等を通じて、人材育成を推進する。

Key points of the space basic plan process chart (revised in Reiwa 3)

Reiwa 3rd year (2021) December 28th
Cabinet Office
Space Strategy / Promotion Bureau

<Recent situation>

<Points for revising the process chart>

Point 1. Ensuring space security

- The role of space in security is expanding.
- For example, in the United States, hypersonic gliding vehicles (HGV), etc. are being developed and small satellite constellations are being developed as a countermeasure; there is also an acceleration of space systems construction

- Conduct research regarding satellite constellations for missile defense, etc., especially related to the demonstration of hypersonic gliding bullet (HGV) detection and tracking.
- A new Space Operations Group (tentative name) will be created (within the Self-Defense Forces), and the space situational awareness system will be put into actual operation from 2023. The national government will strengthen its space monitoring system, such as launching a space status monitoring satellite by 2026.
- Steadily develop space systems such as quasi-zenith satellite systems, information gathering satellites, and communication satellites.

Point 2. Contribution to disaster countermeasures, national resilience and resolution of global issues

- Disaster countermeasures and national resilience are urgent issues; contributions by space systems are possible.
- **To achieve carbon neutrality in 2050, there are expectations for contributions from space.**

- By 2025, build Japan's unique small radar (SAR) satellite constellation capable of high-frequency observation. Demonstrate use by related ministries and agencies, accelerating satellite deployment by domestic operators.
- **Each ministry will work together to promote the realization of space solar power generation. Concerning microwave-type space solar power generation technology, the aim will be to demonstrate by 2025 energy transmission from low earth orbit to the ground.**
- Formulate and promote an international greenhouse gas observation mission concept utilizing satellites, etc., based on the Paris Agreement by countries around the world. Aim to use this system it to confirm the reduction effect of climate change measures.

Objective:
LEO to Ground Microwave
SPS / WPT Demo by 2025

Point 3. Creation of new knowledge through space science and exploration

- Mars exploration programs in Europe, the United States, China, etc. are becoming very active.
- There is a need to steadily proceed with the Artemis program.

- Regarding lunar exploration by the Artemis program – such as Gateway equipment developme ... zed rover), etc. – work in collaboration with the private sector to build essential for lunar activity sys ... be the first non-American to land on the Moon, aim for the realization of landing on the moon by a Jap ...
- Launch the Martian Moons EX Project (MMX) spacecraft in 2024 to realize the first sample return from the Martian sphere for humankind in 2029.

Point 4. Realization of economic growth and innovation driven by space

- There is an expanding role for space infrastructure in supporting the digital transformation.
- Improving the institutional environment for new space activities is a necessity.

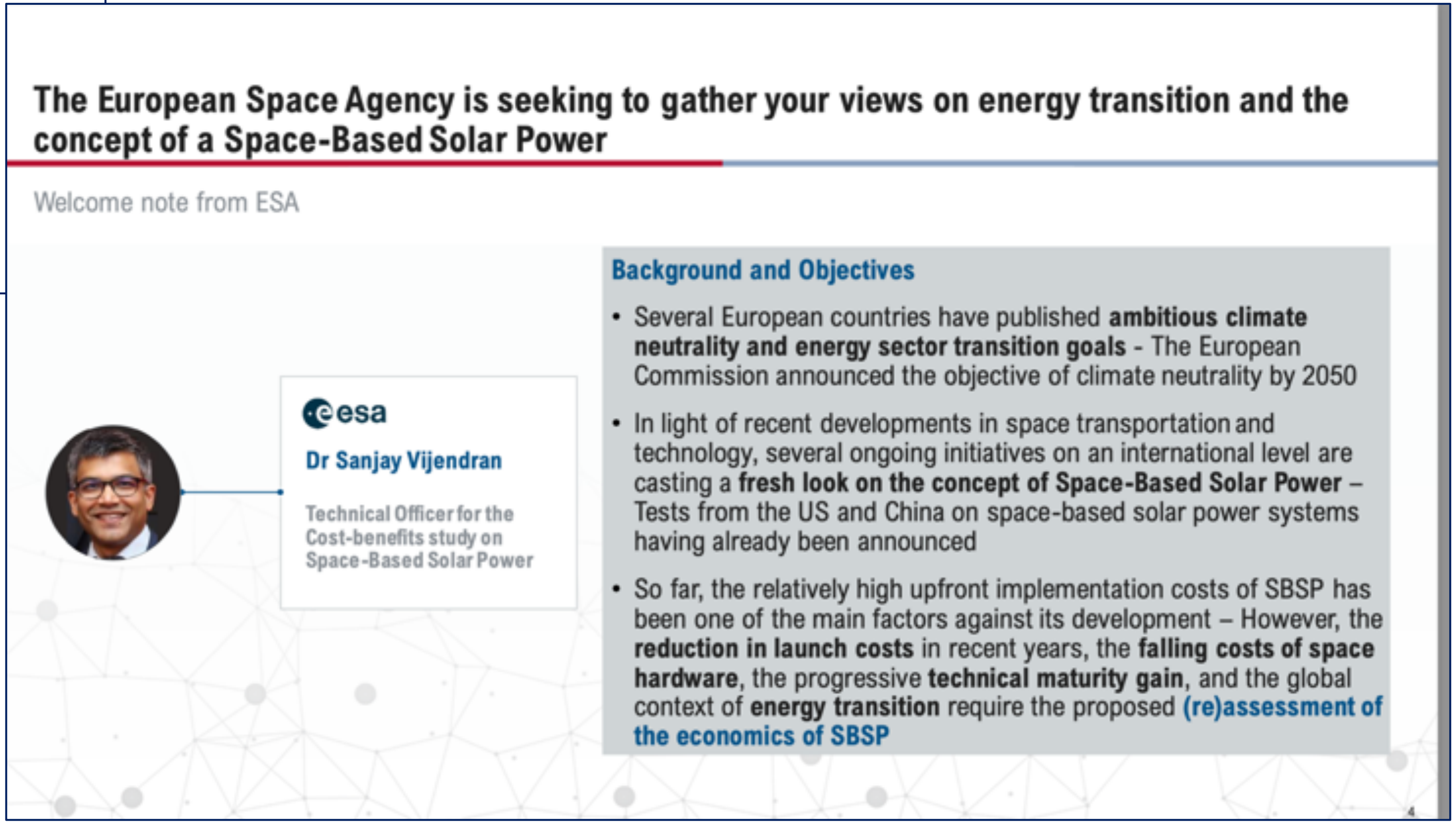
- Intensive data utilization solutions that will help solve regional issues in collaboration with local governments, etc., in order to expand the use of satellite data. Promote development and demonstration.
- Develop the necessary institutional environment (with a view to cooperation with the United States) to become a core base for space business in Asia by developing spaceports, etc.
- During 2021, work to formulate a medium- to long- term policy on international norms regardIng general orbital use rules.

Point 5. Strengthening the comprehensive foundation that supports Japan's space activities, including the industrial and scientific technology infrastructure

- Next-generation space technology (such as optical communication) is indispensable for both commercial and security space and is becoming more and more important for economic security.
- International efforts are accelerating the increased use of small satellite constellations overseas.

- Low-Earth orbit satellite-to-satellite optical communication, in-orbit autonomous control technology, etc., are important basic technologies for next-generation small satellite constellations; Japan will make efforts to acquire and launch a demonstration satellite as soon as possible.
- Japan will promote R&D for a future space transportation system through public-private co-creation. aiming to achieve drastic cost reduction, etc., while taking into account international market trends,
- Exchange of satellite data on climate change risk and sustainable use of oceans and marine resources in the four countries of Japan, the United States, Australia and India. We will proceed with discussions on capacity building support for countries in the Indo-Pacific region and the creation of international rules.
- Promote human resource development by providing opportunities to participate in space activities such as the development of artificial satellites.

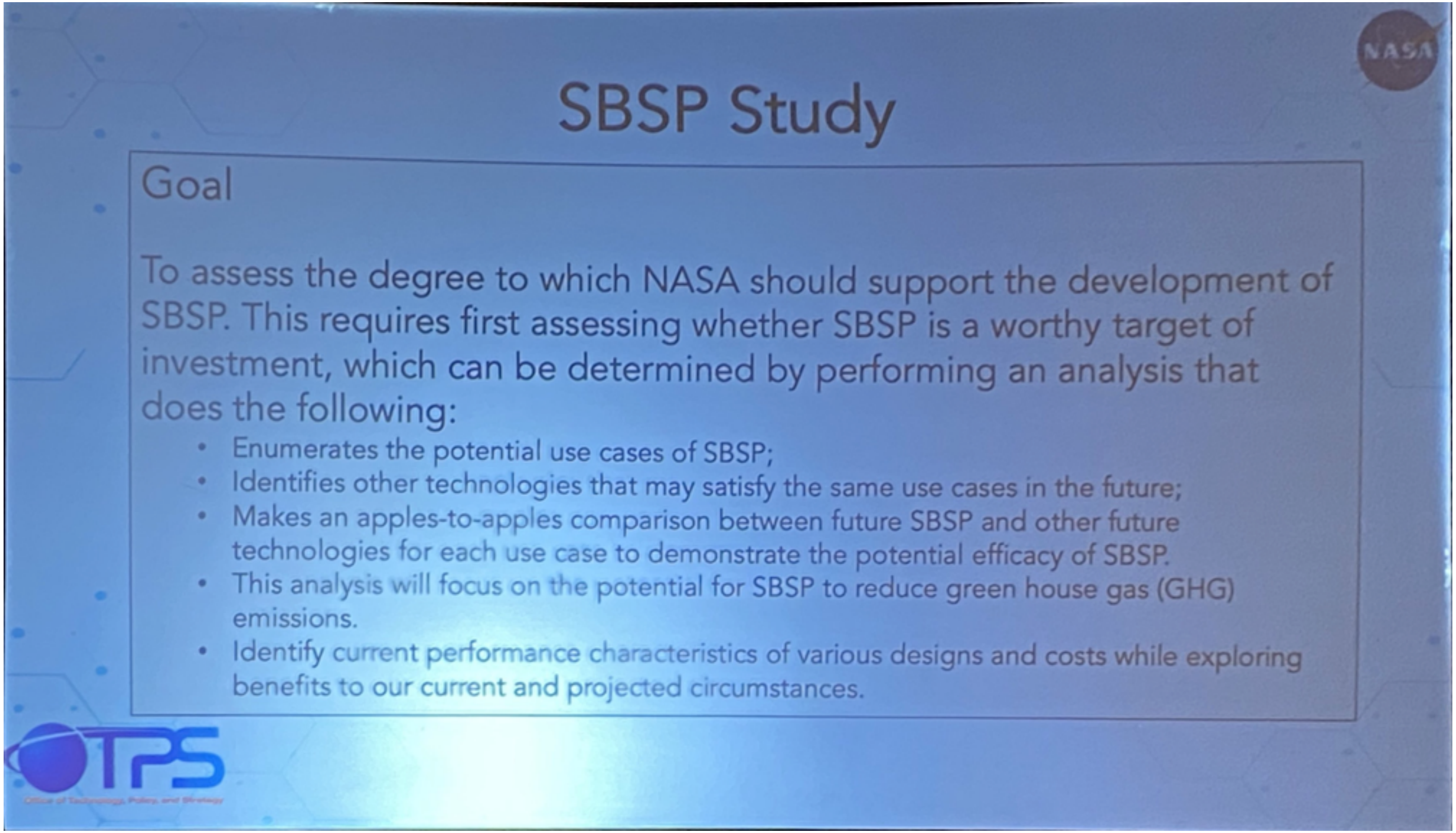
ESA Study – 2022



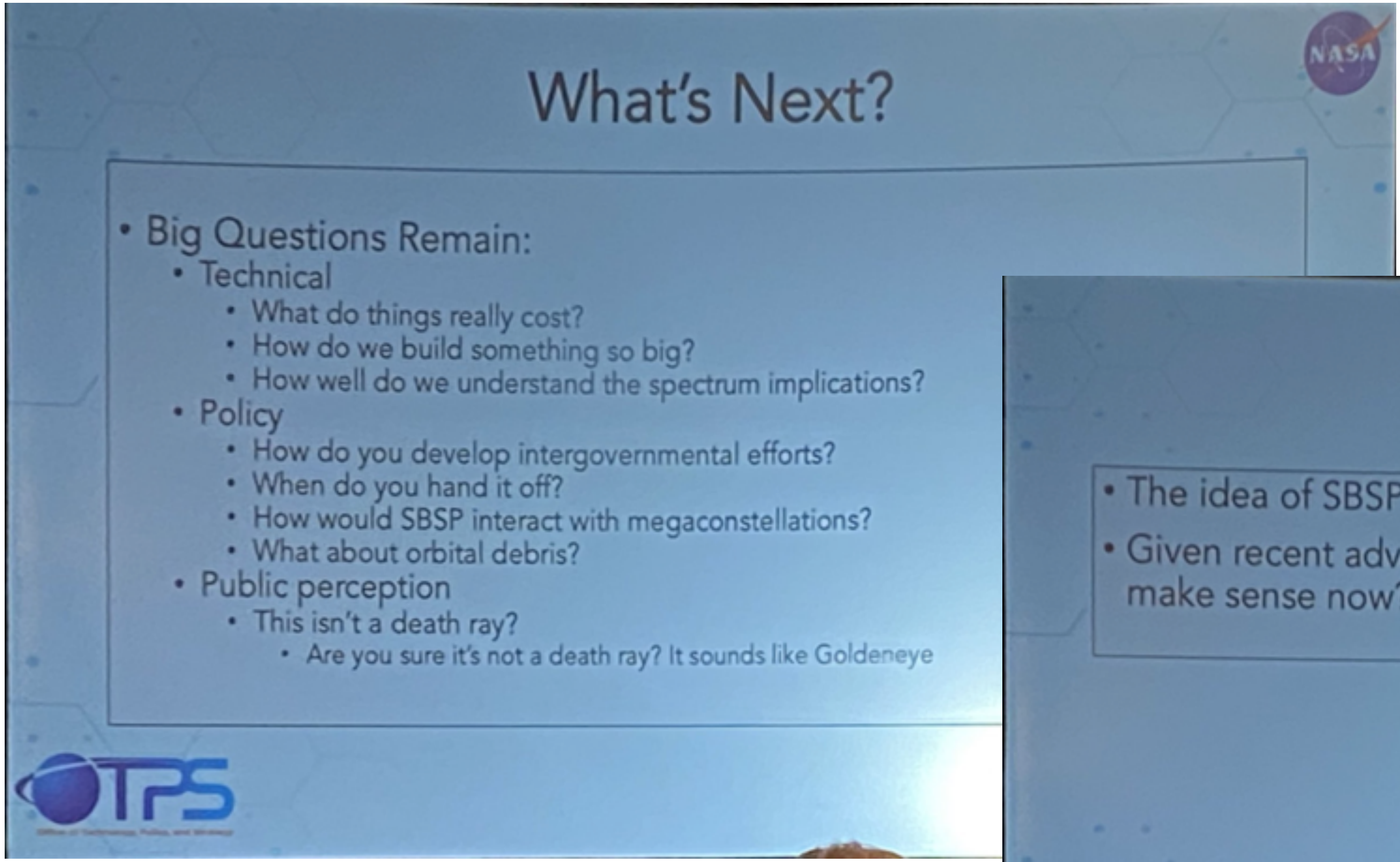
Objective:

Assess the benefits and economics of SPS...

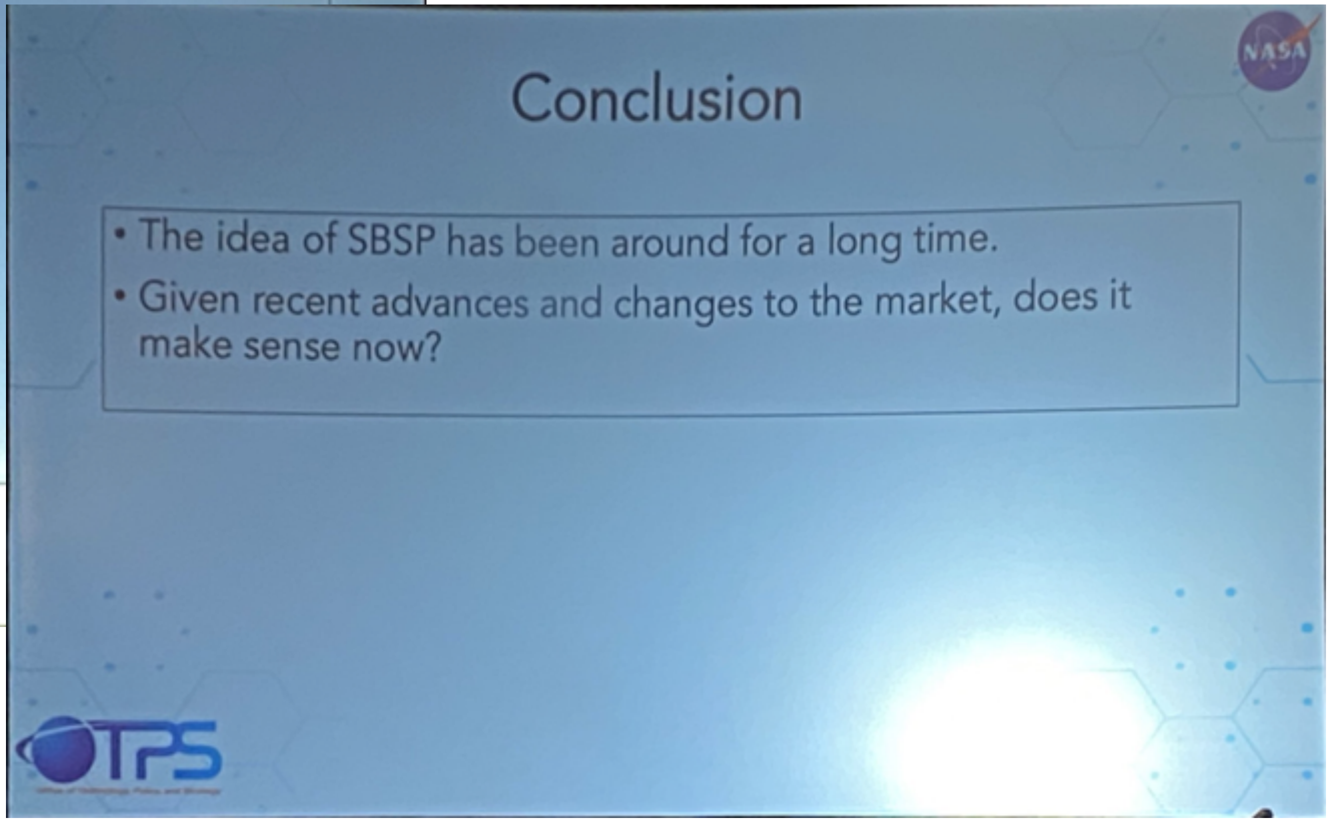
NASA Study – 2022 (1 of 2)



NASA Study – 2022 (1 of 2)



Objective is to Answer the question:
Does (SPS) make sense now?



CitiGroup Assessment of Commercial Space to 2040 (May 2022)

Solar Power from Space: On the Horizon

The energy sector is the world's number one pollutant, responsible for over 30% of global greenhouse gas emissions. Space-based solar power (SBSP) could support the existing cleantech revolution and help nations to tackle climate change and meet the 1.5°C target set by the Paris Agreement.

According to the U.S. Department of Energy, the amount of power from the sun that strikes the Earth in an hour is more than what the entire world consumes in a year (430 quintillion joules). The technology to collect and use space solar power is already possible; however, high launch costs have been the key hindrance. We believe that lower launch costs mean that space-based solar power is now on the horizon.

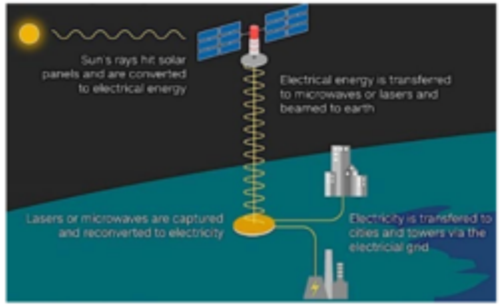
The key advantages to solar power generation in space are its higher collection rate due to no atmosphere, and the possibility of placing a solar collector in an orbiting location where there is sun 24 hours a day. Additionally, it bypasses the considerable fraction of solar energy (~55%–60%) that is lost on its way through the Earth's atmosphere by the effects of reflection and absorption, and solves the problem of energy storage as the continuous stream of power from the sun means that energy will be available when needed.

How Space-Based Solar Power Could Work

Space-based solar power systems will likely consist of:

1. Reflectors or inflatable mirrors installed on satellites in orbit, which will concentrate energy from the sun onto either solar cells or heaters (for thermal systems)
2. Antennas to wireless transmit power to Earth either via microwave or laser
3. A rectifying antenna (rectenna) on Earth to collect the waves of electromagnetic radiation and convert them into electricity to be distributed on the grid

Figure 76. How Space-Based Solar Power Could Work



Source: CNN, U.S. Department of Energy

"We forecast that space-based solar power will be worth $23 billion in annual sales by 2040..."

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

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

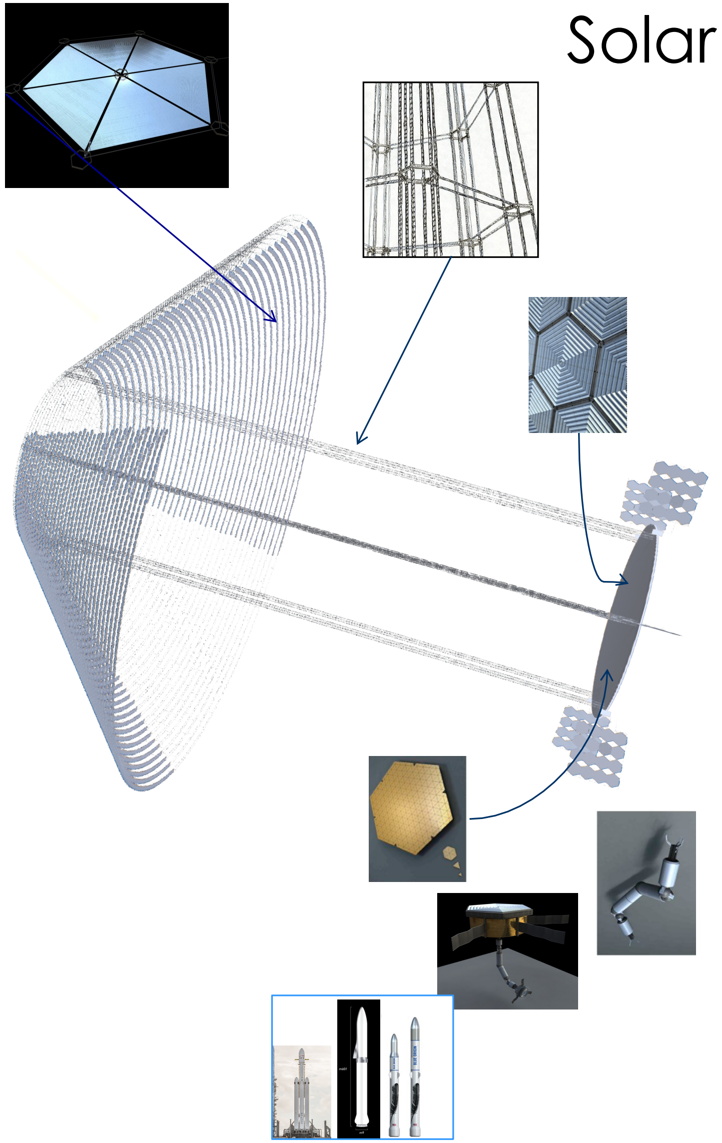
Diverse genetic "individuals" in a single community comprising 100s of species and many 1000's of individuals

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

This is the most promising type of SPS

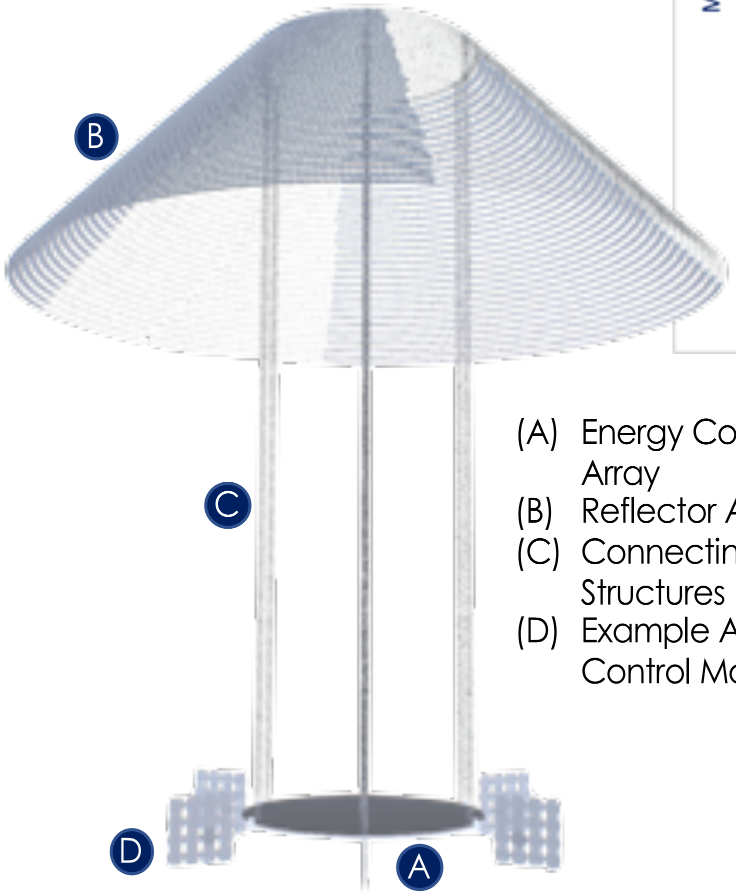
One Example: SPS-ALPHA

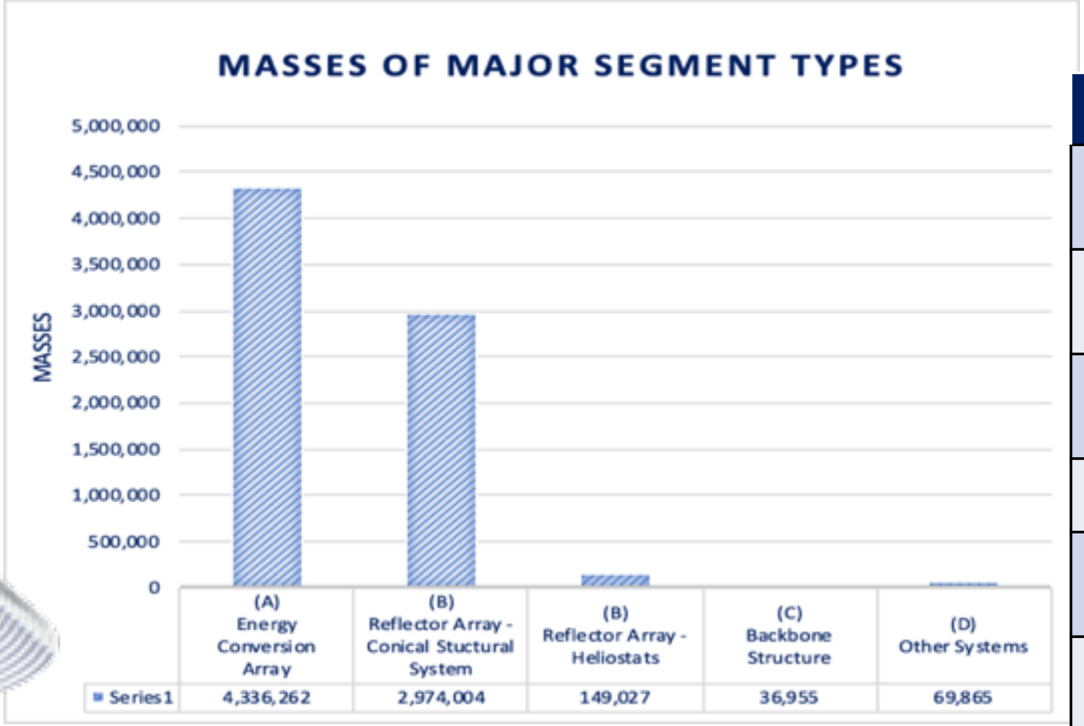
Solar Power Satellite via Arbitrarily Large Phased Array



- 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 OVERVIEW

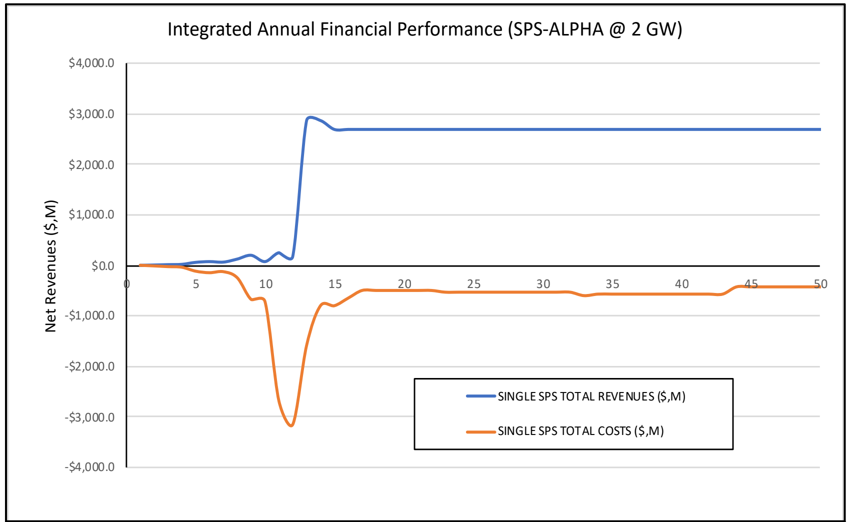


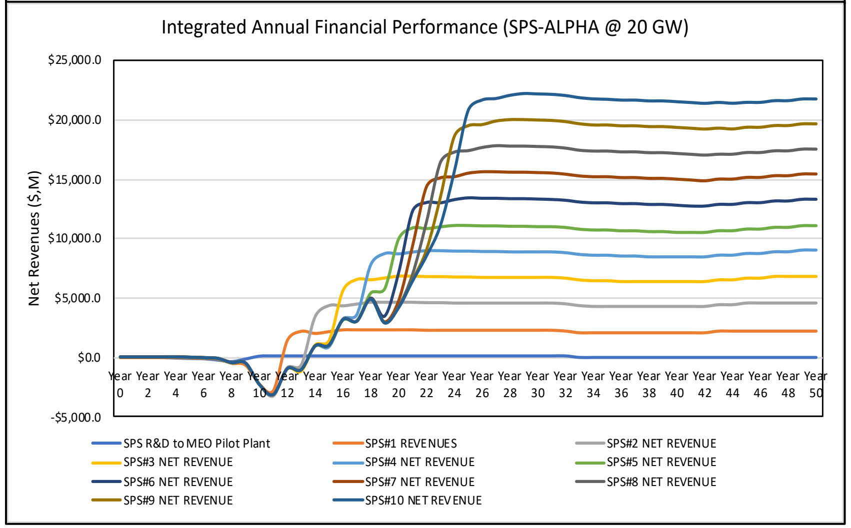


(A) Energy Conversion Array
(B) Reflector Array
(C) Connecting Boom Structures
(D) Example Attitude Control Modules

	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

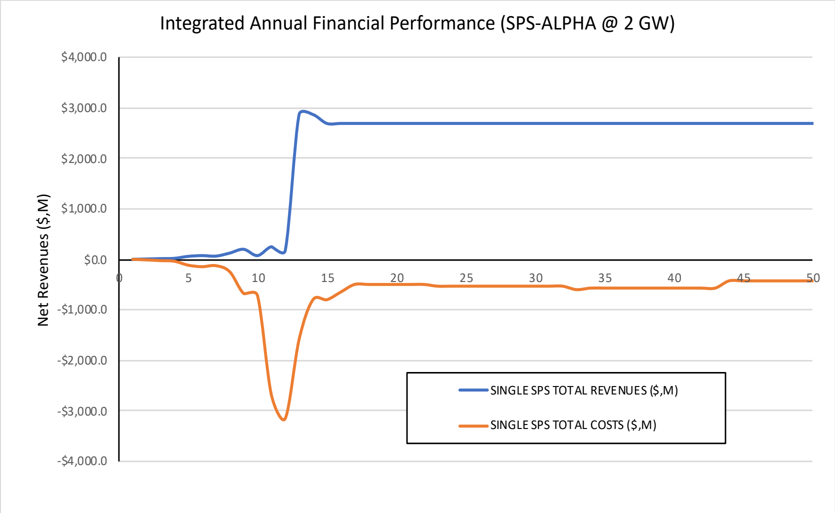
SPS-ALPHA Business Case and Economics (1 of 2)

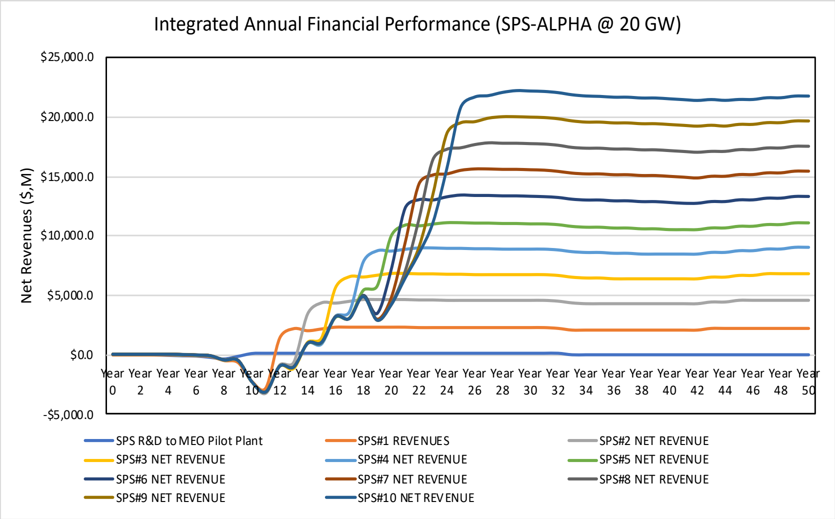




- Assuming a deployment of ~20 GW (10 platforms) of SPS-ALPHA, delivering power terrestrially to some 30 ground receivers
- Economic analysis period of ~50 years, beginning with the first year of R&D
- The key performance parameters underlying these economics include:
- Cost of R&D (through MEO Pilot Plant, described below) @ $1.3B
- Cost of SPS-ALPHA number 1 construction and deployment (including 3 ground receivers and one energy storage system) @ $7.6B
- Beginning of electricity NET sales at about $2B / year (beginning in year 12);

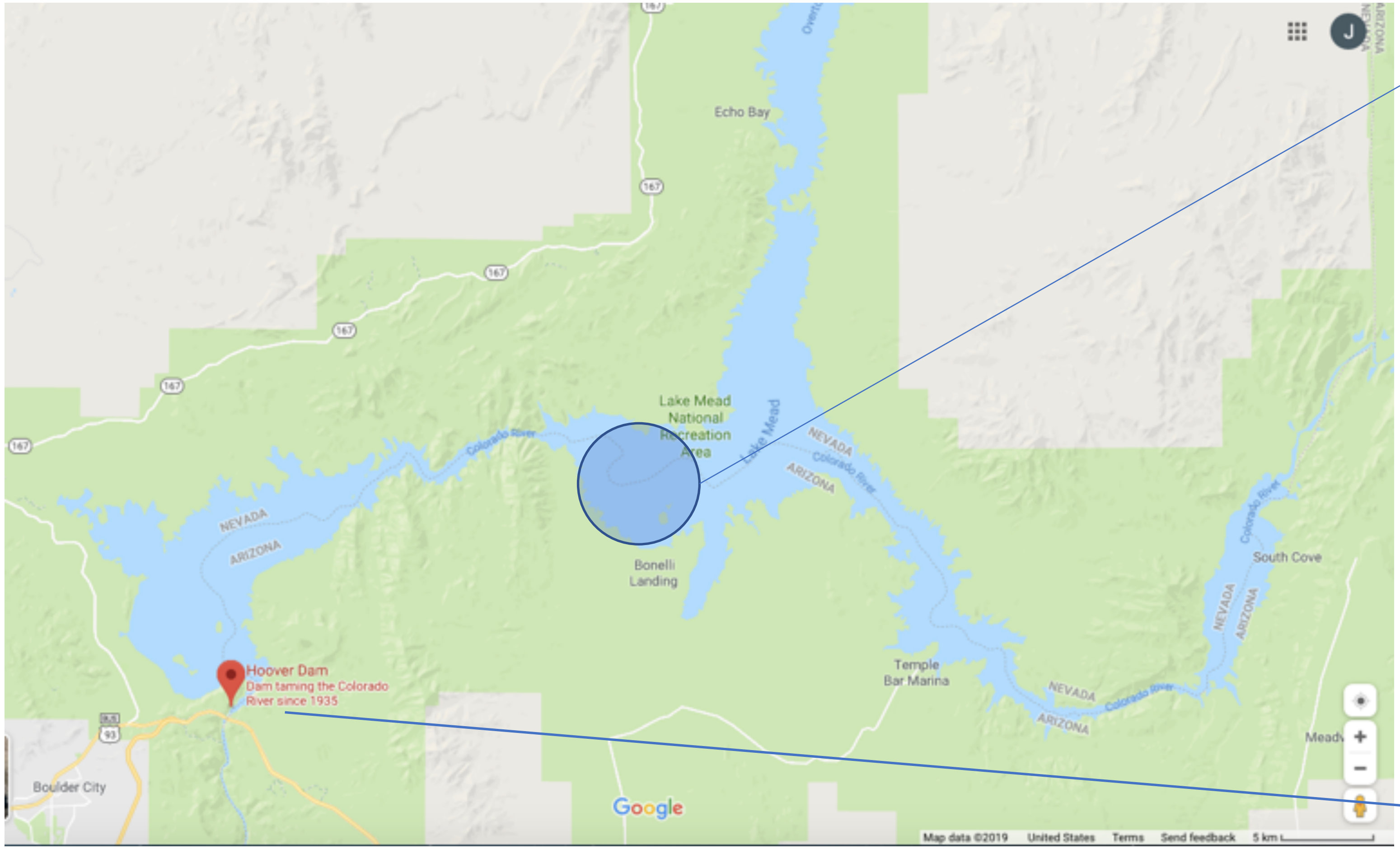
SPS-ALPHA Business Case and Economics (2 of 2)





- LCOE was calculated at ~4.6¢/kWh, with a projected wholesale price of electricity of $154 / MWh – including sales to
  - Baseload markets @ 8¢/kWh (45%),
  - Commercial markets @ 5¢/kWh (45%), and
  - Premium markets @ 20¢/kWh
  - With a 'zero-carbon surcharge' (i.e., a subsidy) assumed at 5¢/kWh.
- The resulting economic performance for a single platform (3 receivers) is then:
  - IRR: ~20.2%
  - Costs per SPS
    - Then-Year: $ 31.4B; NPV: $ 19.5B
  - Gross Revenues per SPS:
    - Then-Year: $ 104.9B; NPV: $ 57.1B
  - Net Revenues per SPS
    - NPV: $ 57B
- Energy Return on Energy Invested: >95:1; Payback: ~60 days

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)

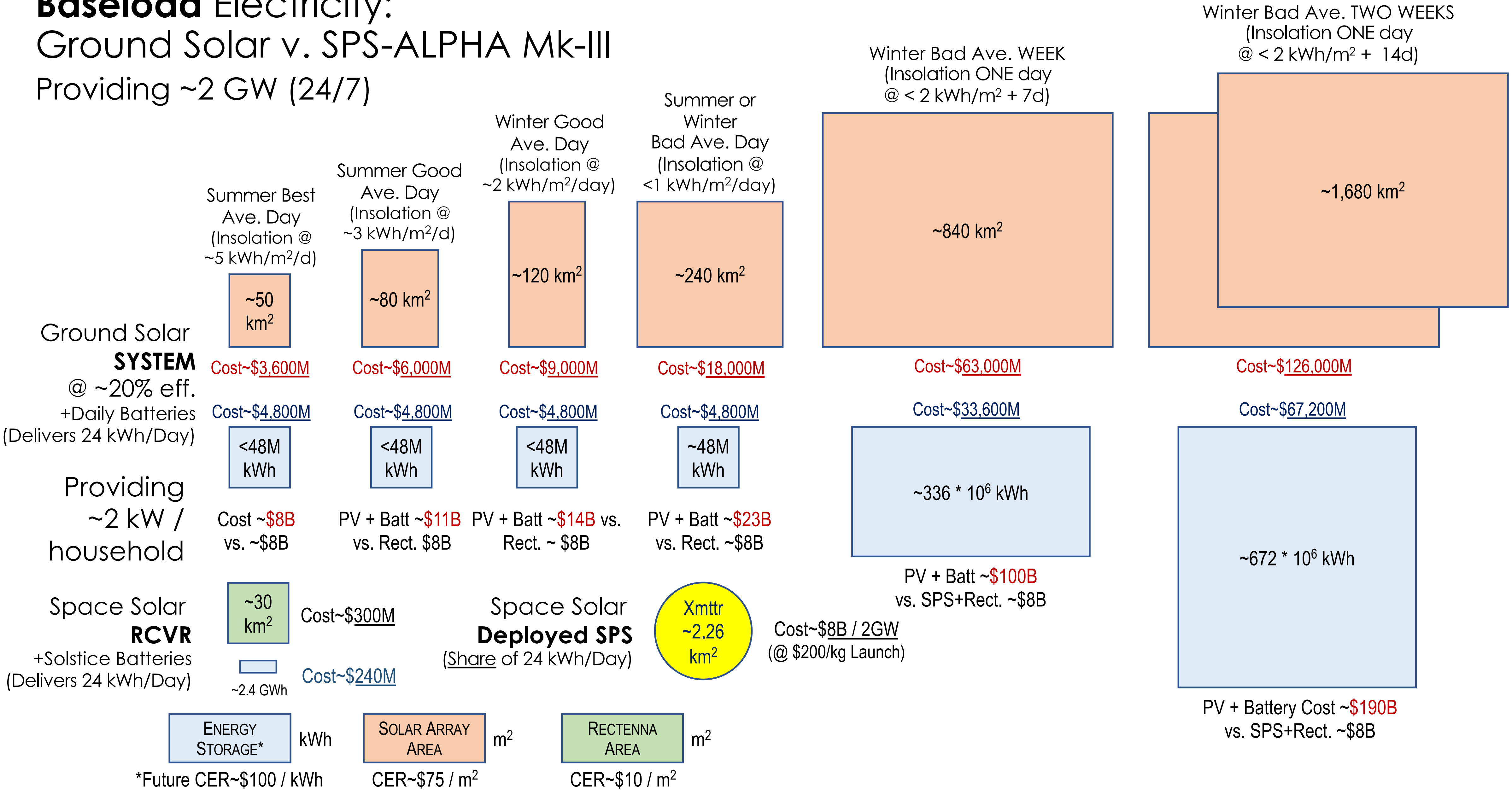
Annual Energy: ~4,000 GW-hours

Dam Investment: ~$ 50M c. 1931

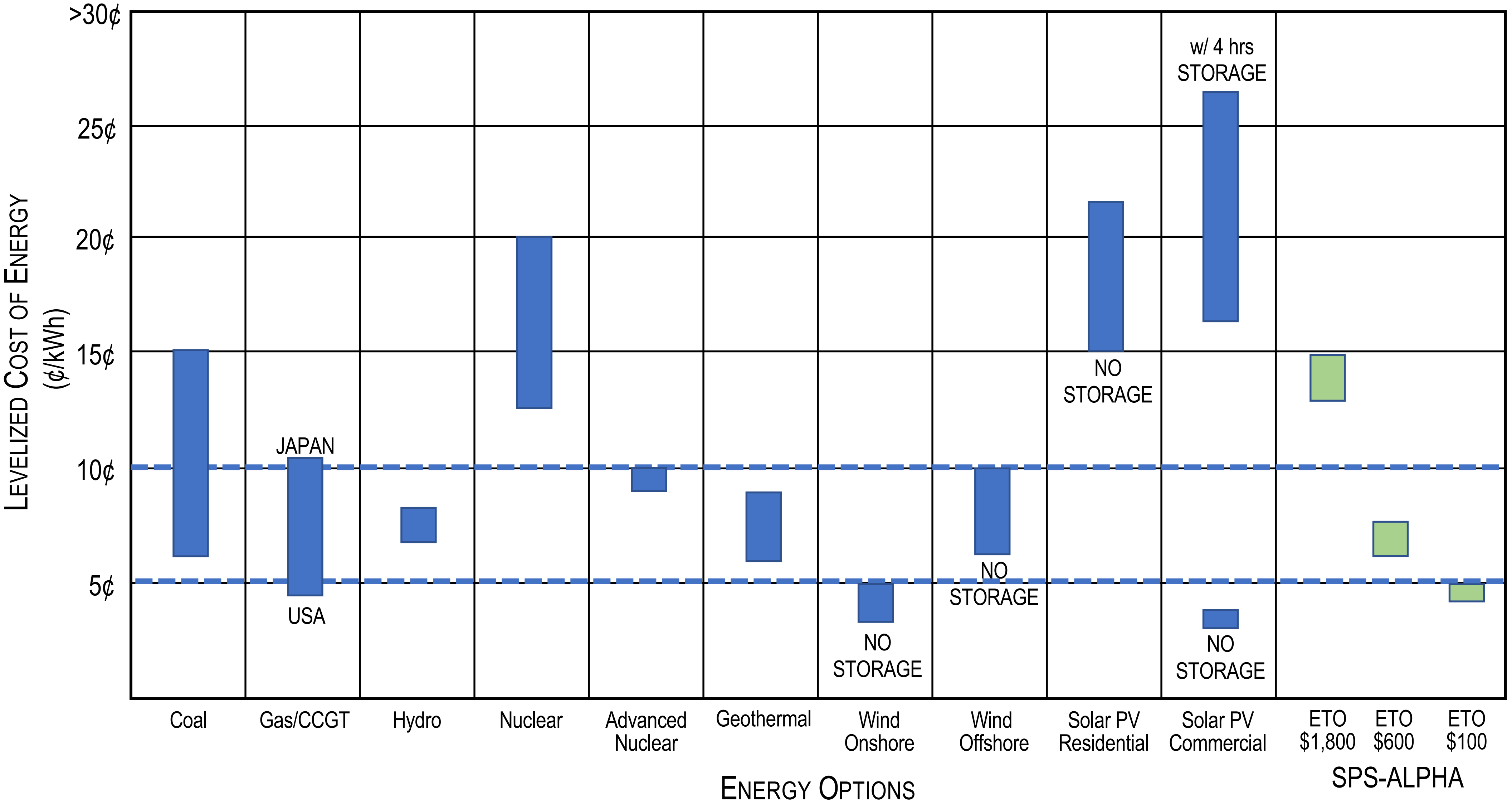
Ref: https://en.wikipedia.org/wiki/Hoover_Dam (19 Jan '22)

Baseload Electricity: Ground Solar v. SPS-ALPHA Mk-III

Providing ~2 GW (24/7)



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



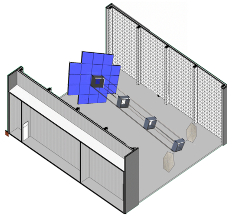
Outline

- 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**

A Practical Near-Term Roadmap to SPS

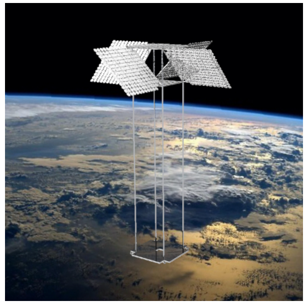
Opportunity for the US to

- Lead the International Community
- Establish "rules of the road"
- Create a New Industry: Commercial Space Solar Power



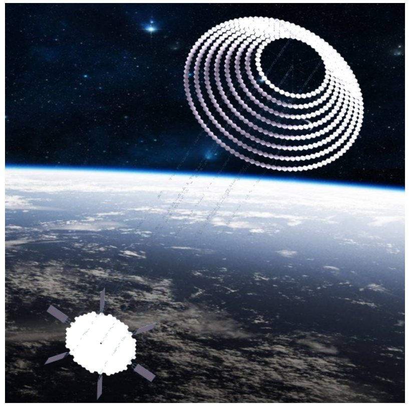
Phase 1

Lab Prototype
@ ~50kW
~$40M
12-18 months



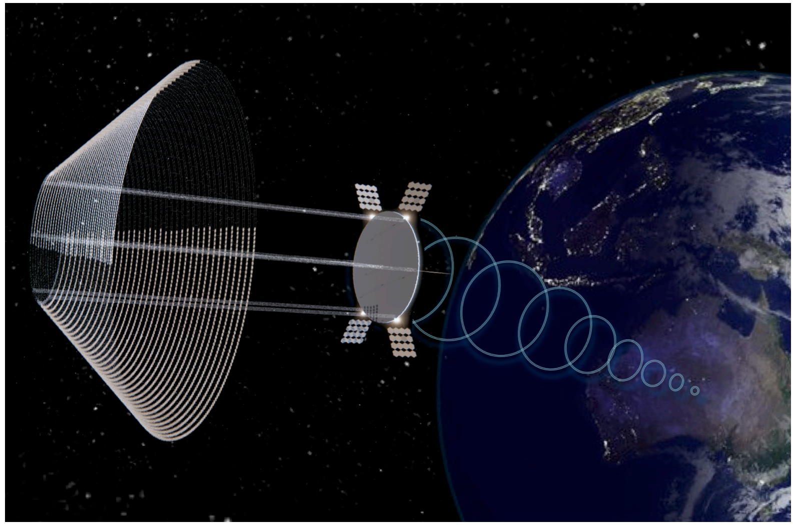
Phase 2

LEO Demonstration
@ ~300kW
~$250M
+18-24 months



Phase 3

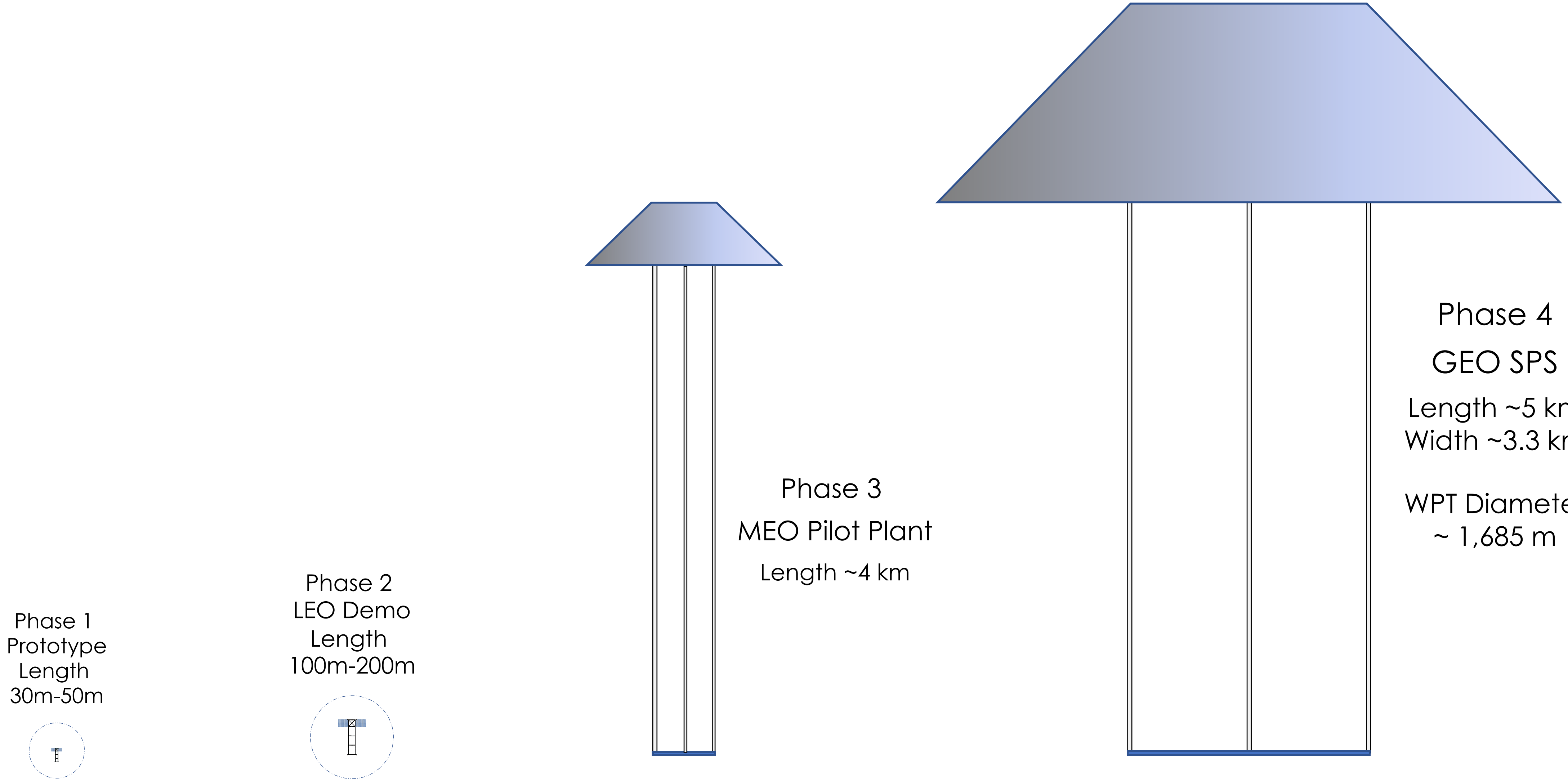
MEO Pilot Plant
@ 10-100MW
+$1B-$2B
+24-36 months



Phase 4 / 5+

Operational SPS in GEO
@ 1-2GW
+$10B-$12B
+36-60 months,

Scaling **UP**: Size Comparisons



Potential "First System"