CASSIOPEIA SOLAR POWER SATELLITE Dispatchable Green Energy From Space CSAR, Cambridge -May 2023

Presentation · May 2023

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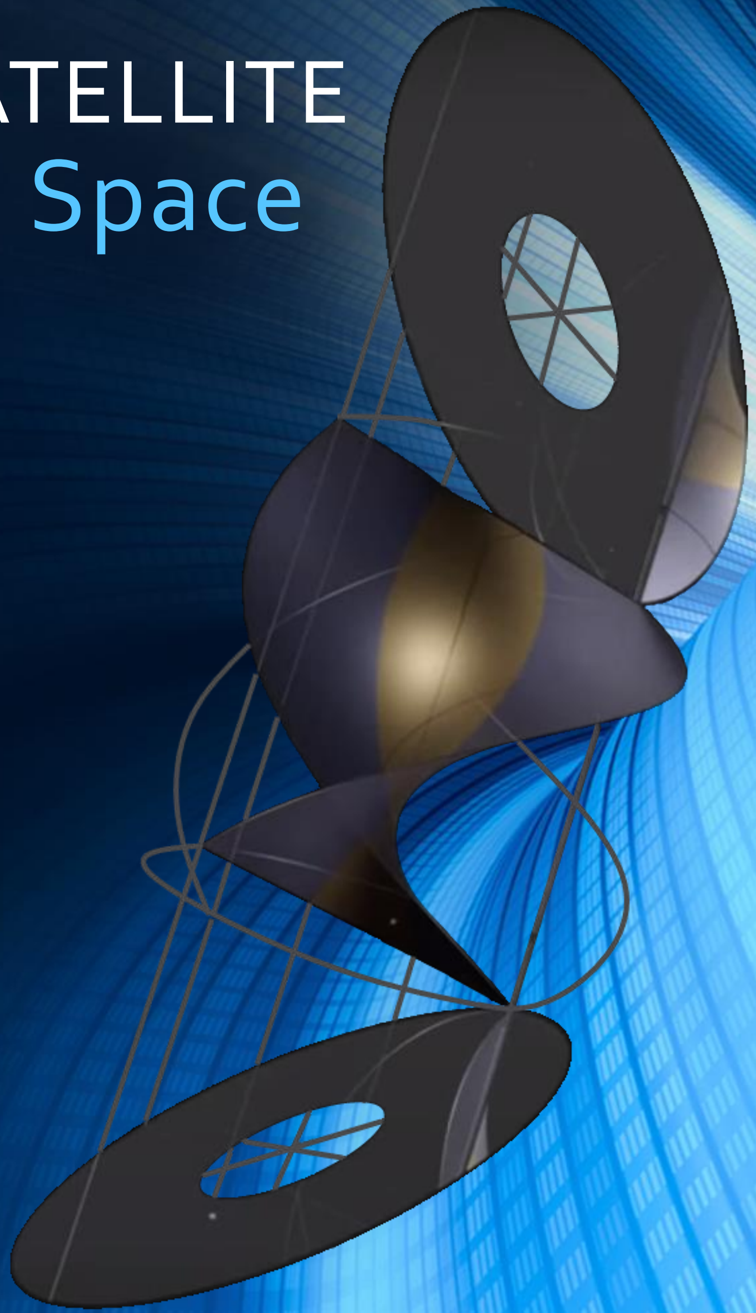
Ian Cash
International Electric Company Limited

CASSIOPeiA Solar Power Satellite
Dispatchable Green Energy From Space

Space Energy Initiative



Ian Cash M.Eng

INTERNATIONAL ELECTRIC

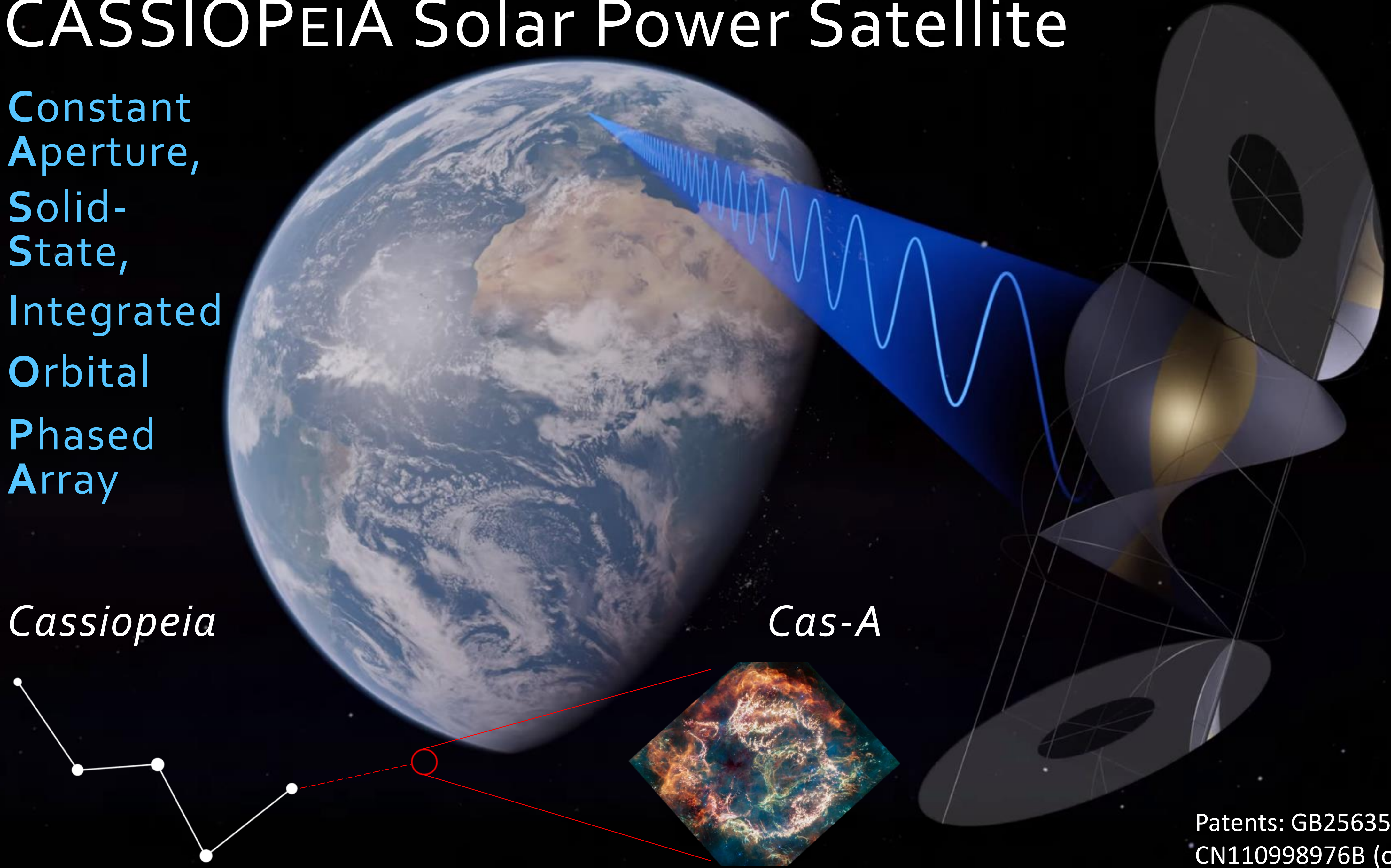
CSAR, Cambridge – May 2023

Space Energy Initiative : 82 Current Members

AIRBUS	ALDEN	ALPINE	Amphenol MILITARY & AEROSPACE	ARCHANGEL LIGHTWORKS	AXIOM SPACE
Capgemini	cfms	CITY UNIVERSITY OF LONDON	CGI	CST	CATAPULT Compound Semiconductor Applications
deimos	Deloitte.	Department for Business, Energy & Industrial Strategy	Department for International Trade	D-ORBIT	Durham University
CATAPULT Energy Systems	exotopic	fieldfisher	FootAnstey Powering your ambition	FRAZER-NASH CONSULTANCY	gmv
HEMPSELL ASTRONAUTICS	inmarsat	UKRI Innovate UK	ECL	Imperial College London	ispace
KBR	Lumi	MAGDRIVE	MAPSAT	mtc	METASAT UK
nano avionics	nationalgrid partners	NMIS National Manufacturing Institute Scotland	MDA	NORSS	CATAPULT Offshore Renewable Energy
OXFORD SPACE SYSTEMS	Queen Mary University of London	QUEEN'S UNIVERSITY BELFAST	UK Atomic Energy Authority	Reaction Engines	CATAPULT Satellite Applications
SIRIN Orbital Systems AG	SOLAR SYSTEM RESOURCES CORPORATION	SPACE POWER	SPACE SOLAR	SURREY	SURREY SPACE CENTRE
Swansea University Prifysgol Abertawe	TELEDYNE e2v Everywhereyoulook	ThalesAlenia Space	TTP The Technology Partnership	TWI	UKLSL
UNIVERSITY OF CAMBRIDGE	UNIVERSITY OF Southampton	University of Strathclyde Glasgow	University of Suffolk	UNIVERSITY OF SURREY	VIRTUS SOLIS

CASSIOPEIA Solar Power Satellite

Constant Aperture, Solid-State, Integrated Orbital Phased Array

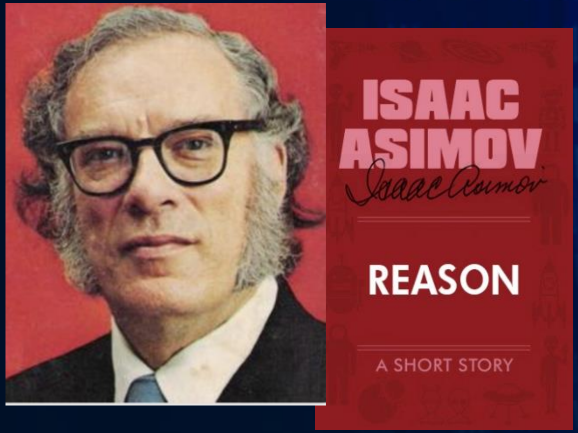


Cassiopeia

Cas-A

Patents: GB2563574, EP3635817, CN110998976B (others pending)

Space Solar Power – Inspiration from Fiction



Isaac Asimov – Reason – 1941

Robots find religion and seize control aboard a Solar Power Satellite beaming energy to Earth. Humanity is ultimately saved by the First Law.

2005

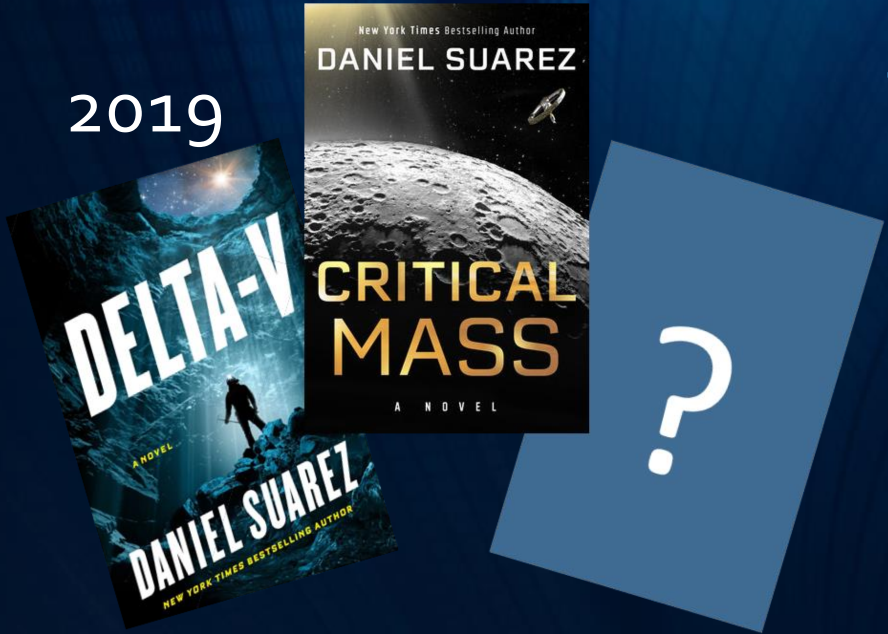
2011

Powersat / Energized

Terrorism and political intrigue set around power satellites, against a background of climate and energy woes

2019

2023

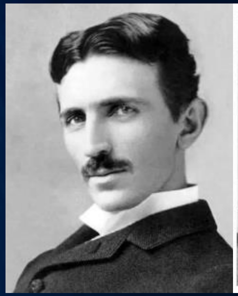


Daniel Suarez

This hard sci-fi trilogy set in the 2030s envisions a plausible trajectory for humanity as a spacefaring civilisation, using the resources of space to solve the challenges on Earth

ECL

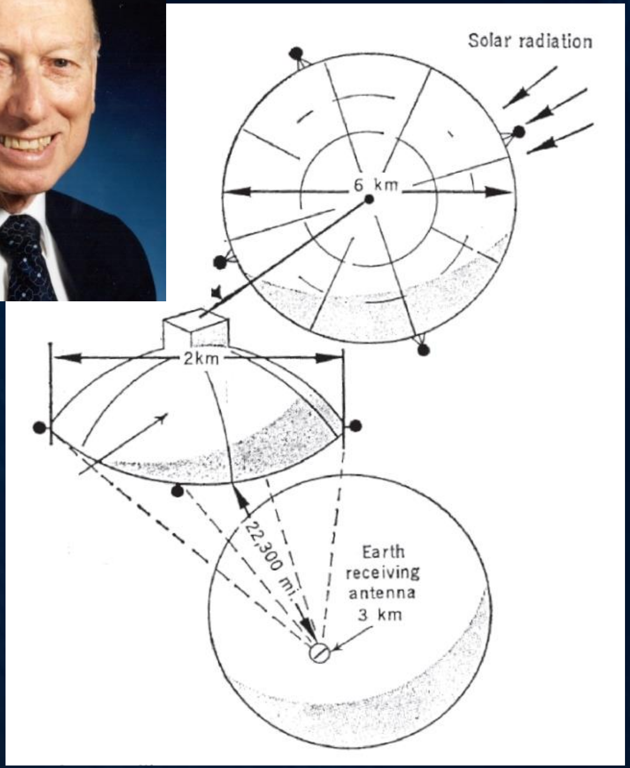
Space Solar Power – Foundations in Science



Nikola Tesla – Wardenclyffe Tower – 1904

Tesla's genius lay more in self-promotion than science. His dream of wireless power delivery was thwarted by his denial of established physics (e.g. James Clerk Maxwell, Guglielmo Marconi), leading to the folly of the Wardenclyffe Tower.

Peter Glaser 1923-2014

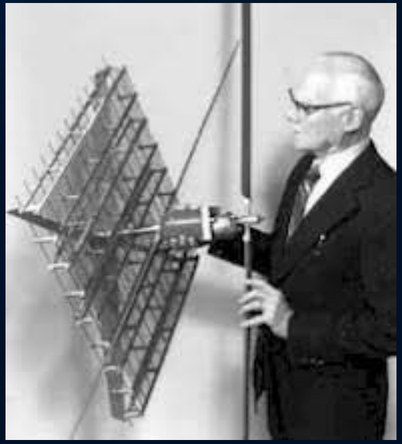


Dr Peter Glaser – Solar Power Satellite Patent - 1968

Peter Glaser invented the first technically-feasible concept of a solar power satellite delivering microwave energy from geo-stationary orbit (GEO) to an Earth-bound rectifying antenna (rectenna). Alongside his colleague William C Brown (inventor of the rectenna) they demonstrated wireless powered flight of a model helicopter and were instrumental in the detailed 1979 Space-Based Solar Power study by NASA/DoE.

Glaser / Brown – Boston Science Museum

William C Brown 1916-1999



International Academy of Astronautics
Permanent Committee for Space Solar Power

March 30th
2023

John C Mankins
Artemis Innovation
United States
(co-Chair, IAA-PCSSP)

Martin Soltau
co-CEO, Space Solar
United Kingdom
(Previous SEI co-Chair)

LI Ming
CAST, China

Koji Tanaka
JAXA, Japan
(co-Chair, IAA-PCSSP)

Xinbin HOU
CAST, China

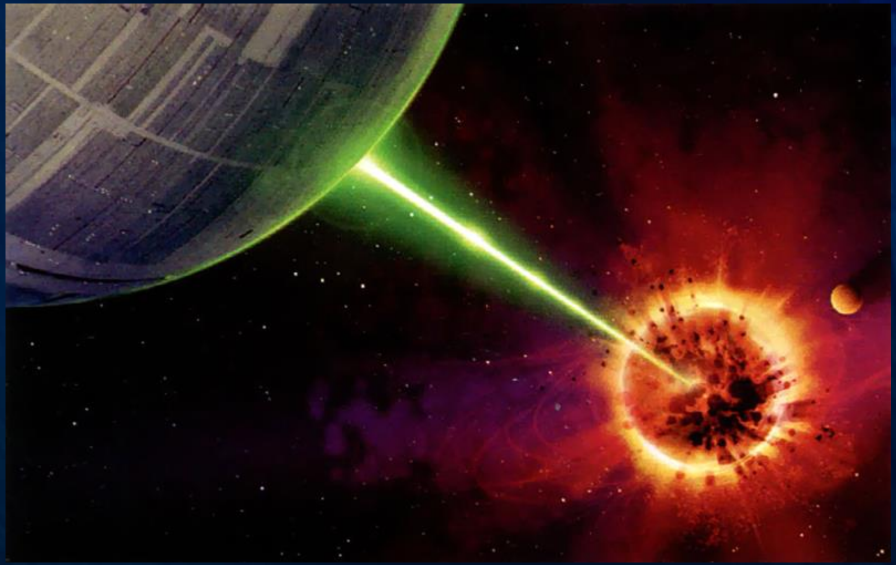
Joon-Min Choi
KARI,
South Korea

Paul Jaffe
Naval Research Labs
United States

Sanjay Vijendran
ESA SOLARIS
Programme Lead

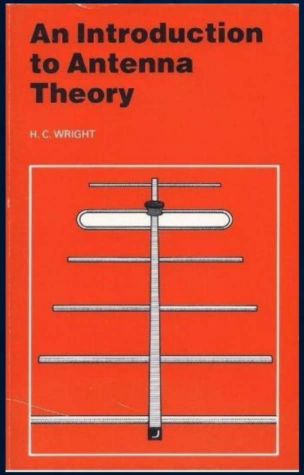
Common Objections to Space Solar Power

It's secretly a space weapon that will vaporise targets



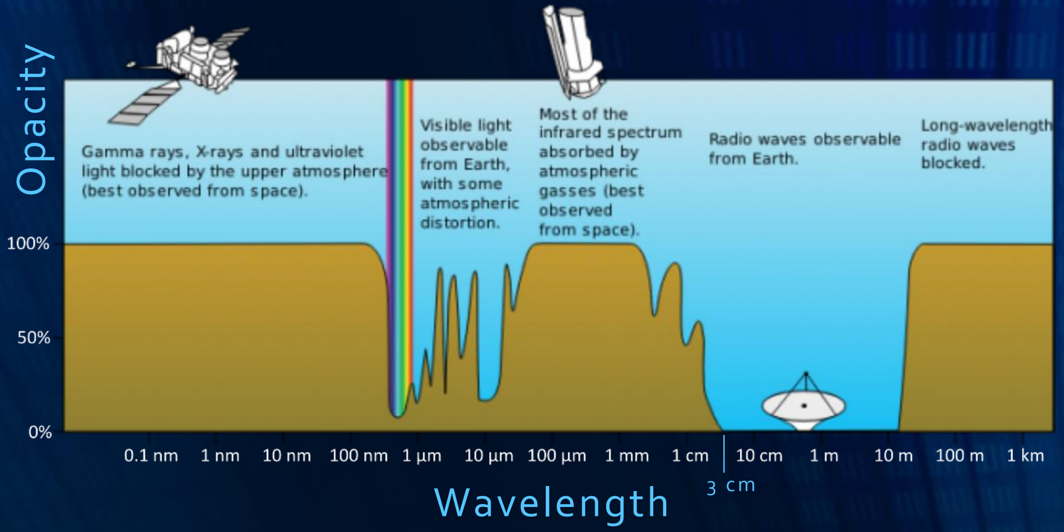
Power from sunlight which would have missed Earth will accelerate Global Warming

The inverse square law means it's feeble and useless across 36,000 kilometres



Wind and terrestrial solar are cheap: why go to space?

RF Safety / Efficacy and Diffraction Physics

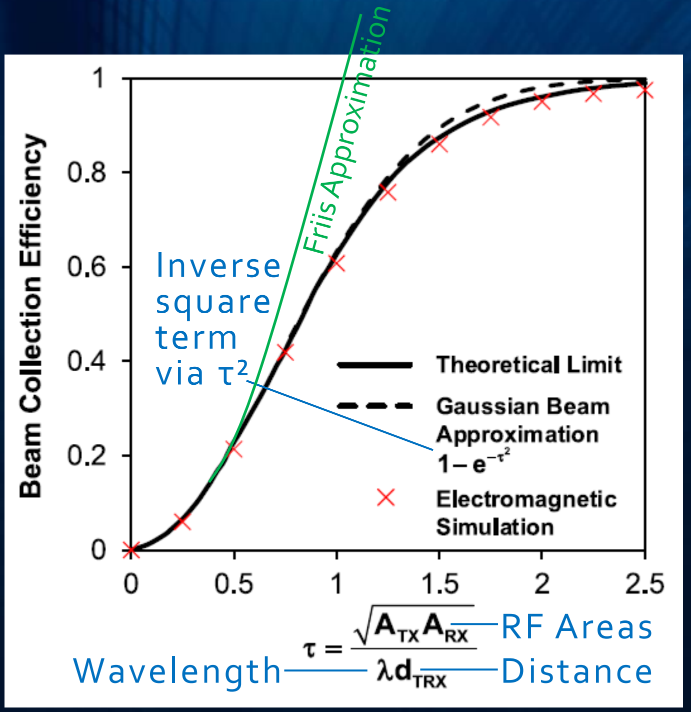


Diffraction physics limits the minimum beam spot size; no “software hack” can lead to unsafe intensity.

A regulatory peak of 230 W/m² (around ¼ sunlight) is likely.

To compete, we want to use wavelengths that pass unimpeded through atmosphere and severe rainstorms (>98% transmission).

This leads to large apertures: very large satellites delivering lots of power – but into large areas at a low, safe intensity.



This same physics allows for high beam collection efficiency, whatever the beaming distance.

Conversion from RF to electrical power is also highly efficient (85-91% since 1975).

Space Solar Power in Perspective – Waste Heat

Thermal Power Plants (Coal, Gas, Fission, Fusion)
The most efficient combined cycle plants achieve approximately 60% thermal efficiency.
For every gigawatt-hour of electrical energy, over **650 MWh** of waste heat is released into the environment.

Terrestrial Solar Farms
Productive solar farms in dry desert regions darken Earth's albedo, leading to more sunlight being thermalised rather than reflected back into space.
Future 30% efficient PV would release **2.3 GWh** of heat for every 1 GWh of electricity produced.

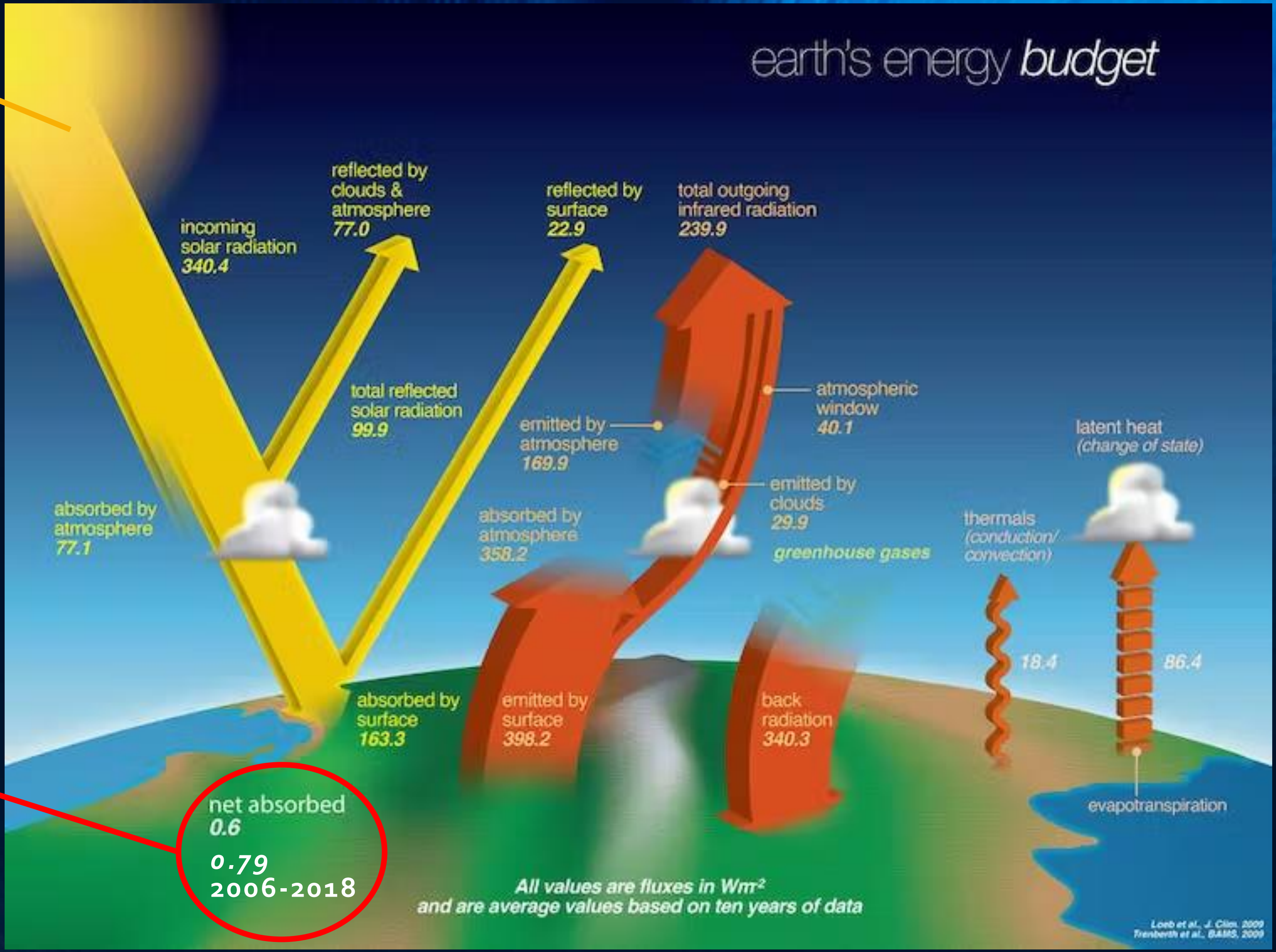
Space Solar Power Rectenna
The type of rectenna used in the 1975 Goldstone power beaming experiment achieved over 91% RF:DC conversion efficiency. In the worst case, such a rectenna (at 85% efficiency, 84% beam intercept during heavy rain) would release **430 MWh** of heat for every 1 GWh of electricity.

Space Solar Power in Perspective – Earth's Energy Budget

174,000 TW continuous insolation

CO_2 280 ppm (pre-industrial)
420 ppm 2022
- 50% increase

Current ~400 TW imbalance due to GHG (anthropogenic)



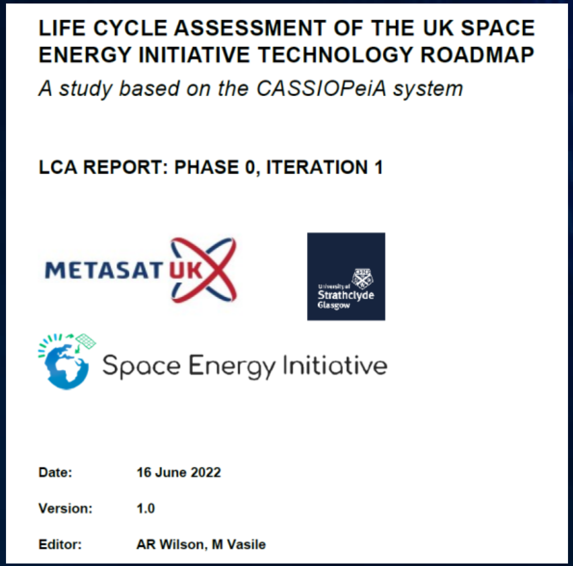
19 TW-year primary energy consumption in 2021, 84% being fossil fuels
(i.e. 16 TW annual average fossil power)

29 TW-year global forecast in 2050

Every TW of fossil power replaced with SSP has 24x benefit

https://theconversation.com/earths-energy-budget-is-out-of-balance-heres-how-thats-warming-the-climate-165244

Space Energy Initiative – Environmental Working Group


LIFE CYCLE ASSESSMENT OF THE UK SPACE ENERGY INITIATIVE TECHNOLOGY ROADMAP

A study based on the CASSIOPeiA system

LCA REPORT: PHASE 0, ITERATION 1

METASAT UK

Space Energy Initiative

Date: 16 June 2022

Version: 1.0

Editor: AR Wilson, M Vasile

Dr Andrew Wilson – MetaSat UK

Preliminary carbon assessment for the gigawatt-scale commercial development programme:
*"Over the lifetime of the programme, the total carbon footprint has been calculated to be **23.6 gCO2e/kWh**, which was found to be similar to other renewable energy technologies"*

Richard Arnold– SLR Consulting

Recent UKSA-funded preliminary work assessing potential rectenna siting and ecological/biodiversity considerations for best implementation


SLRCONSULTING.COM

Space-based Solar Power

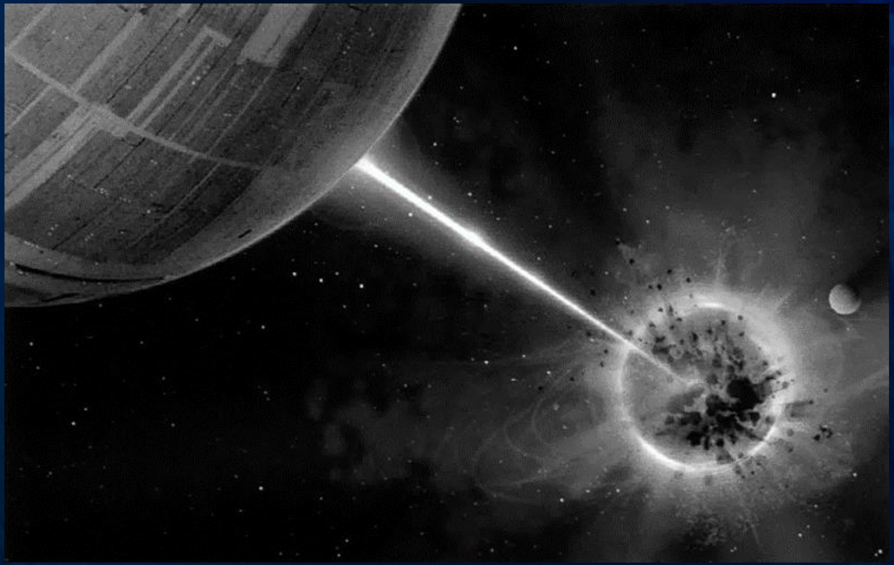
Ecology & Biodiversity

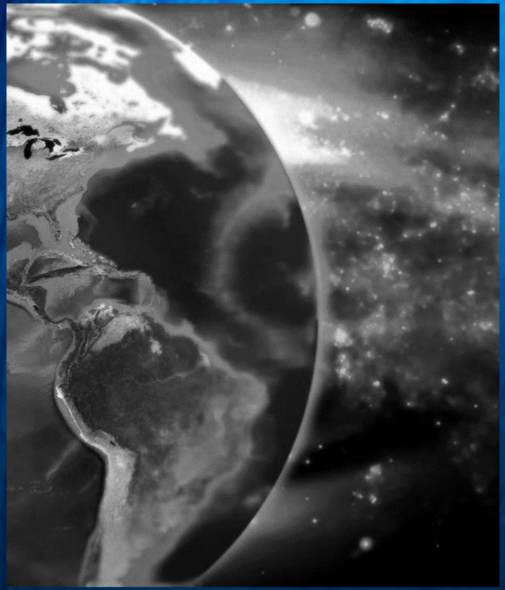
March 2023

SLR

Space Solar Power – What About the Cost?

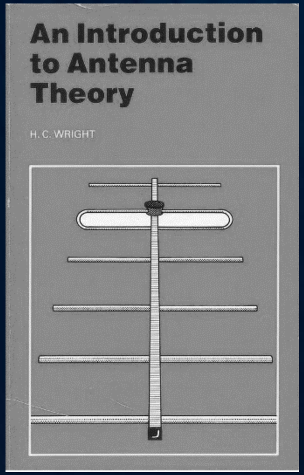
It's secretly a space weapon that will vaporise targets





Power from sunlight which would have missed Earth will accelerate Global Warming

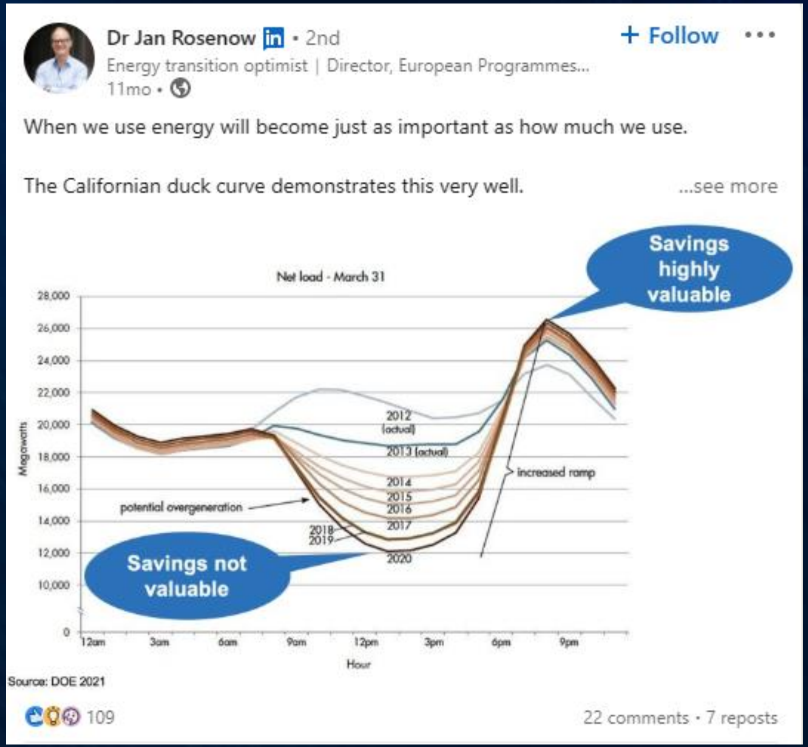
The inverse square law means it's feeble and useless across 36,000 kilometres

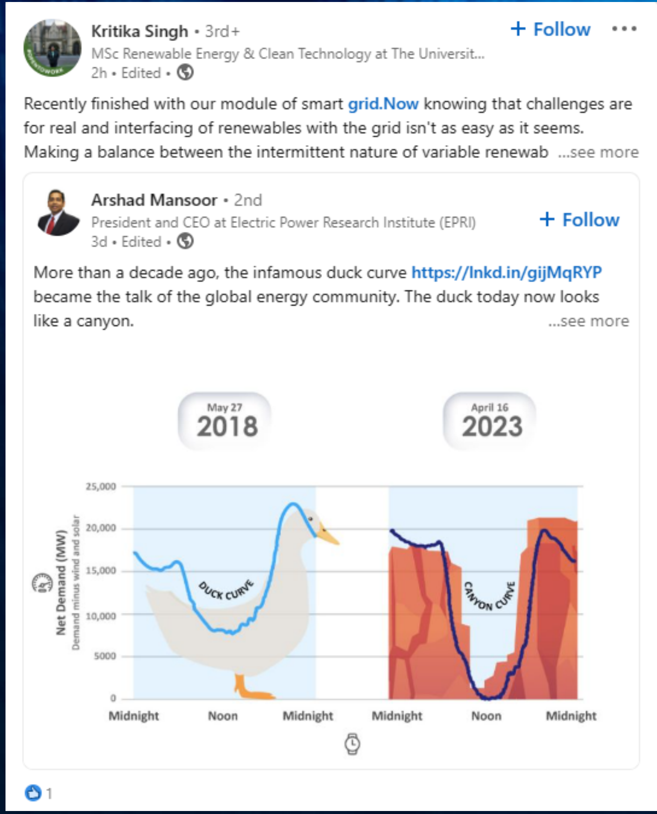


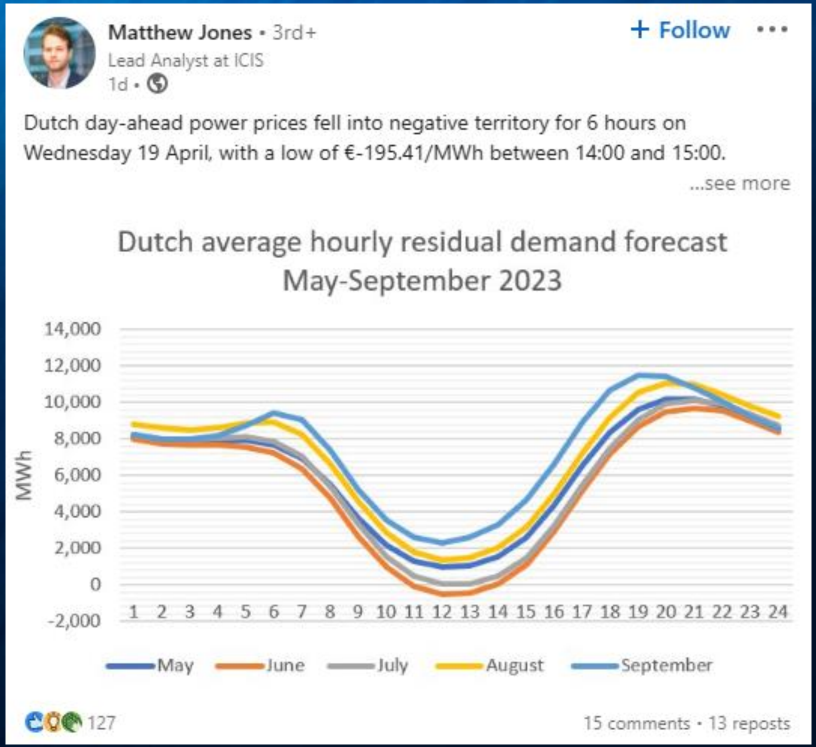
Wind and terrestrial solar are cheap: why go to space?

Are Terrestrial Renewables Cheap?

Overbuild of solar around the globe has led to negative demand – and prices – around local noon. Clearly this is unsustainable for new renewable companies wishing to enter the market.

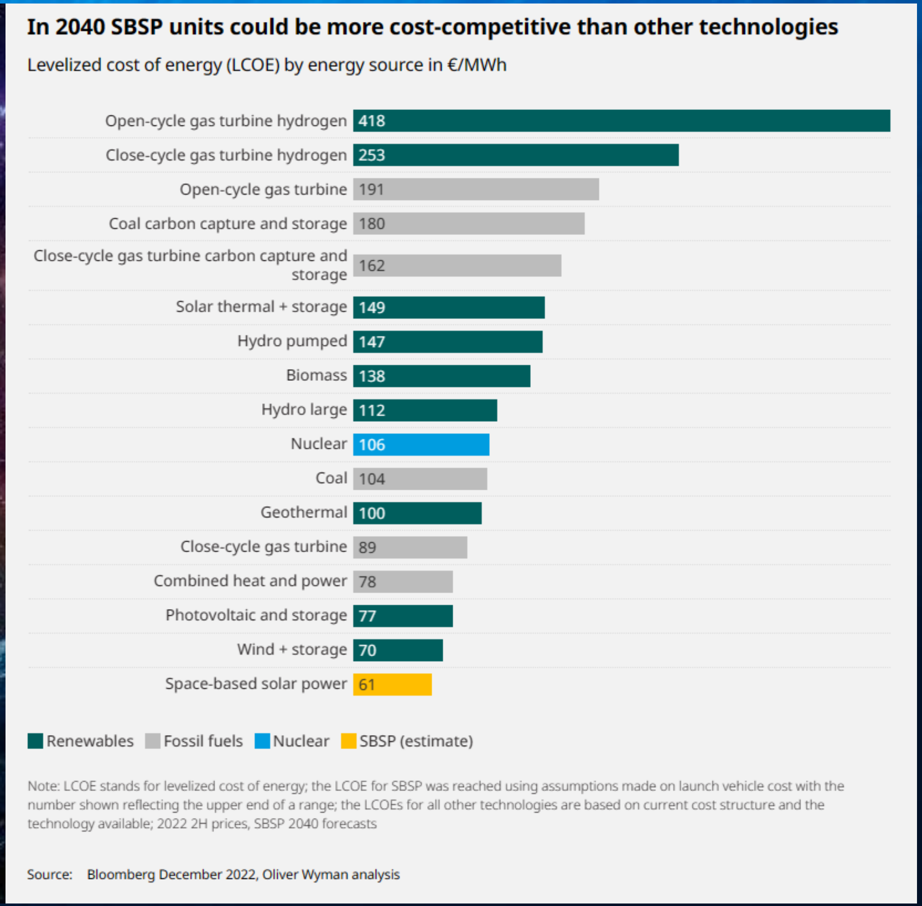






Simple comparisons of LCOE miss the added value of dispatchable power; power which is available when it is wanted and as much as is needed, at minimal notice.

Are Terrestrial Renewables Cheap?

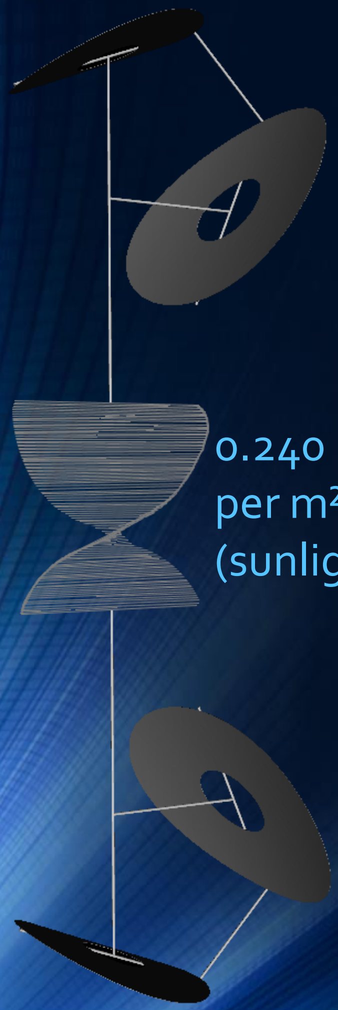


"Several designs are being considered for the space segment, but the most promising option appears to be CASSIOPeiA"

CASSIOPeIA vs Terrestrial PV Power Comparison

"You'd have to convert photon to electron to photon back to electron. What's the conversion rate?" Elon Musk 2012

Per Square Metre of Intercepted Sunlight:



0.240 kg per m² (sunlight)

AM0 ➔ 1365 W(SOLAR)

Concentrator optics (system+microscale): **79.9%**

AzurSpace CP44 PV efficiency at modelled operating temperature: **39.4%**

DC:RF Conversion: **85%**

Beam transmission over 38,500 km, through atmosphere and severe rainstorm, captured at rectenna: **82%**

RF:DC Conversion: **85%**

Delivered ➔ 255 W(DC)

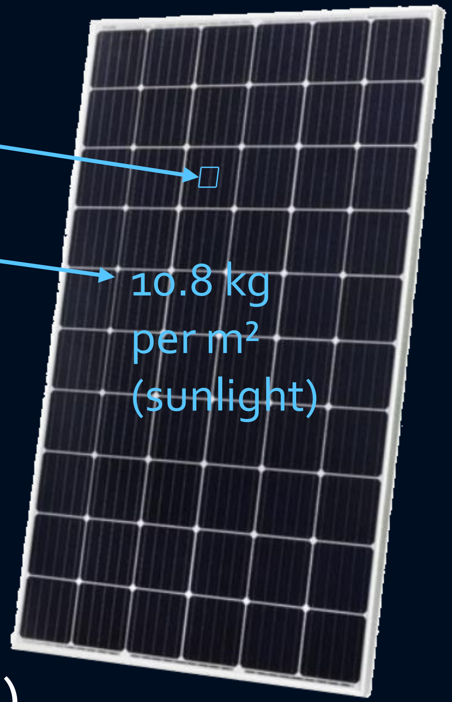
× 500 less PV area

× 45 less mass

12% more power

AM1.5 ➔ 1000 W(SOLAR) = "1-SUN"

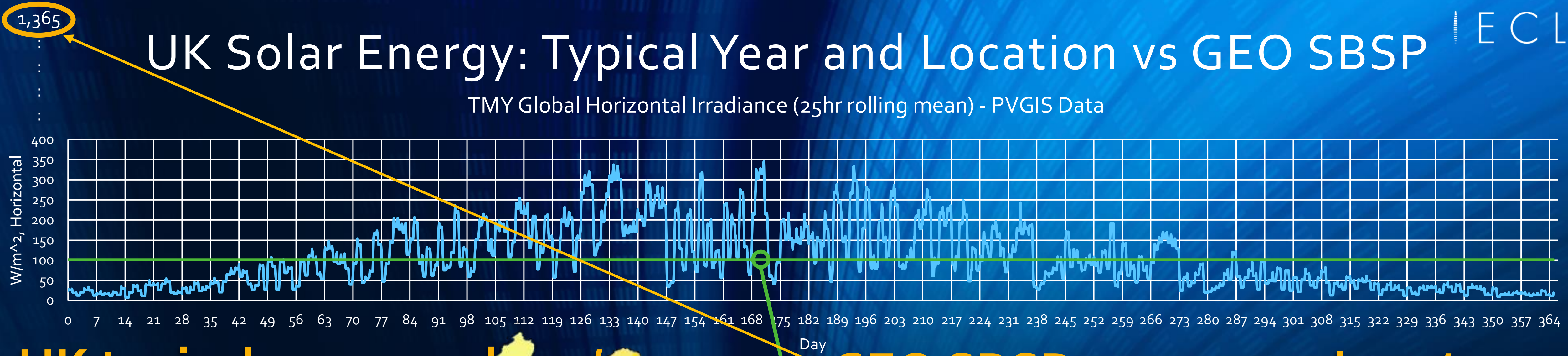
Sunpower Max 3 panel efficiency: **22.8%**



10.8 kg per m² (sunlight)

Delivered ➔ 228 W(DC)

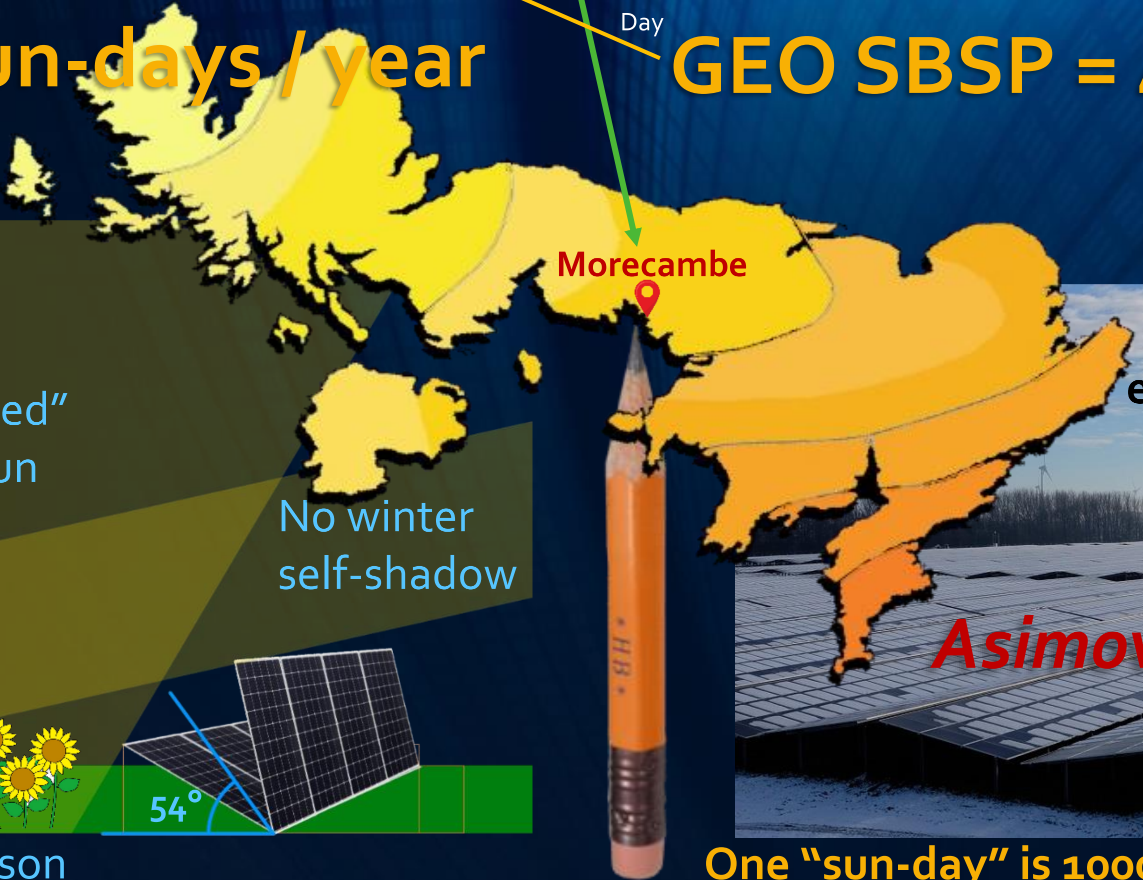
UK Solar Energy: Typical Year and Location vs GEO SBSP



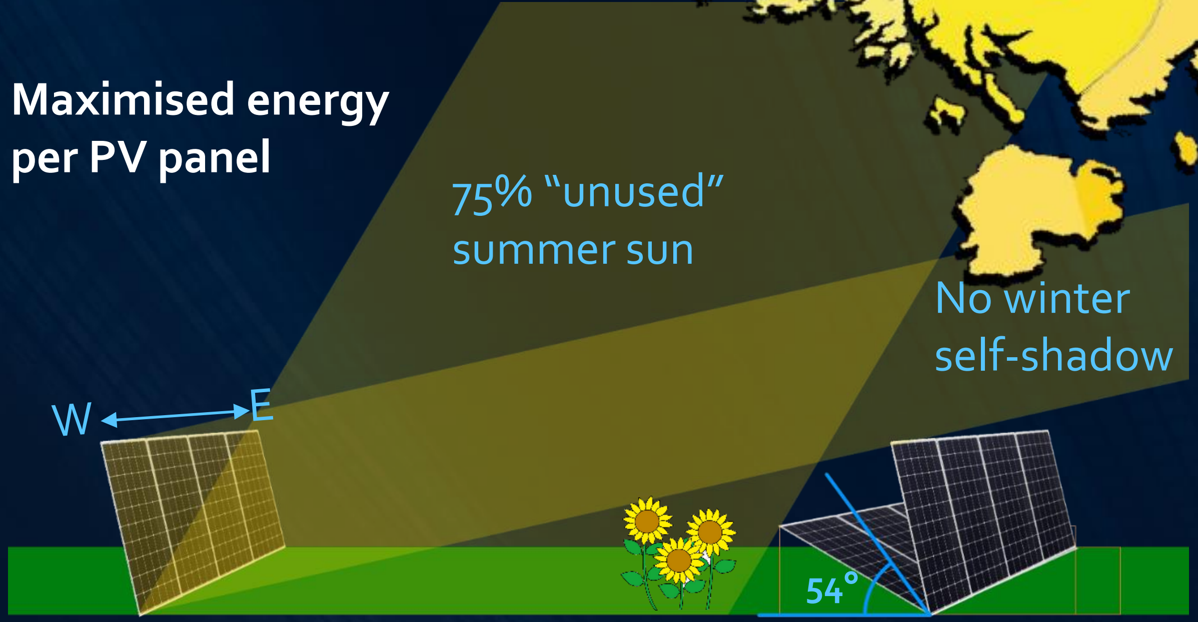
UK typical = 37 sun-days / year

GEO SBSP = 497 sun-days / year

(13× solar available)



Maximised energy per PV panel

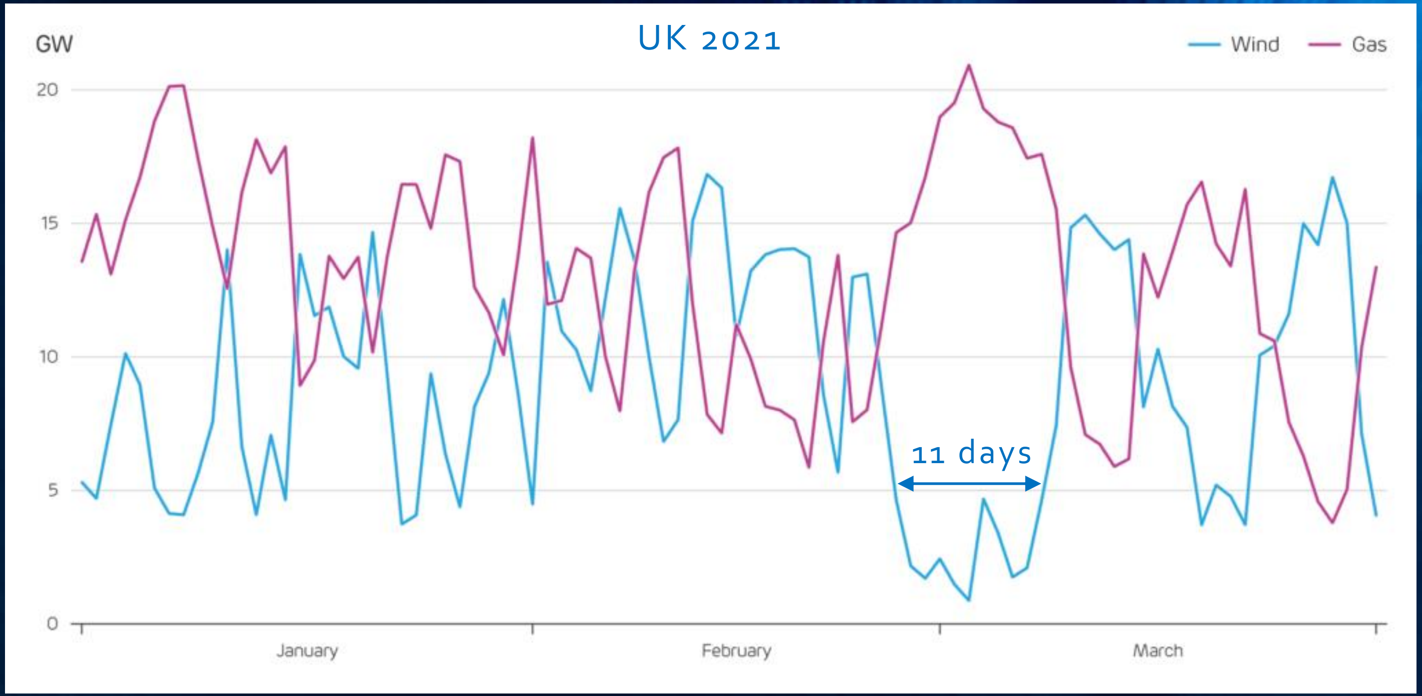


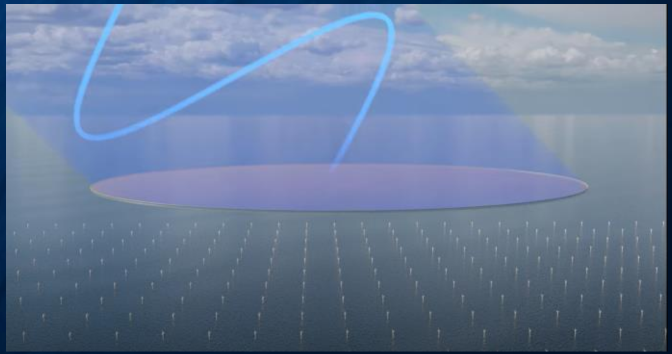
Tilt according to latitude and season

One "sun-day" is 1000 W per square metre for one day

UK Wind Power: Transformation into Firm Baseload Power?

Virtually all grid-scale wind power is currently backed-up by gas-fired power plants. Excess wind capacity is curtailed (wasted).





https://reports.electricinsights.co.uk/q1-2021/when-the-wind-goes-gas-fills-in-the-gap

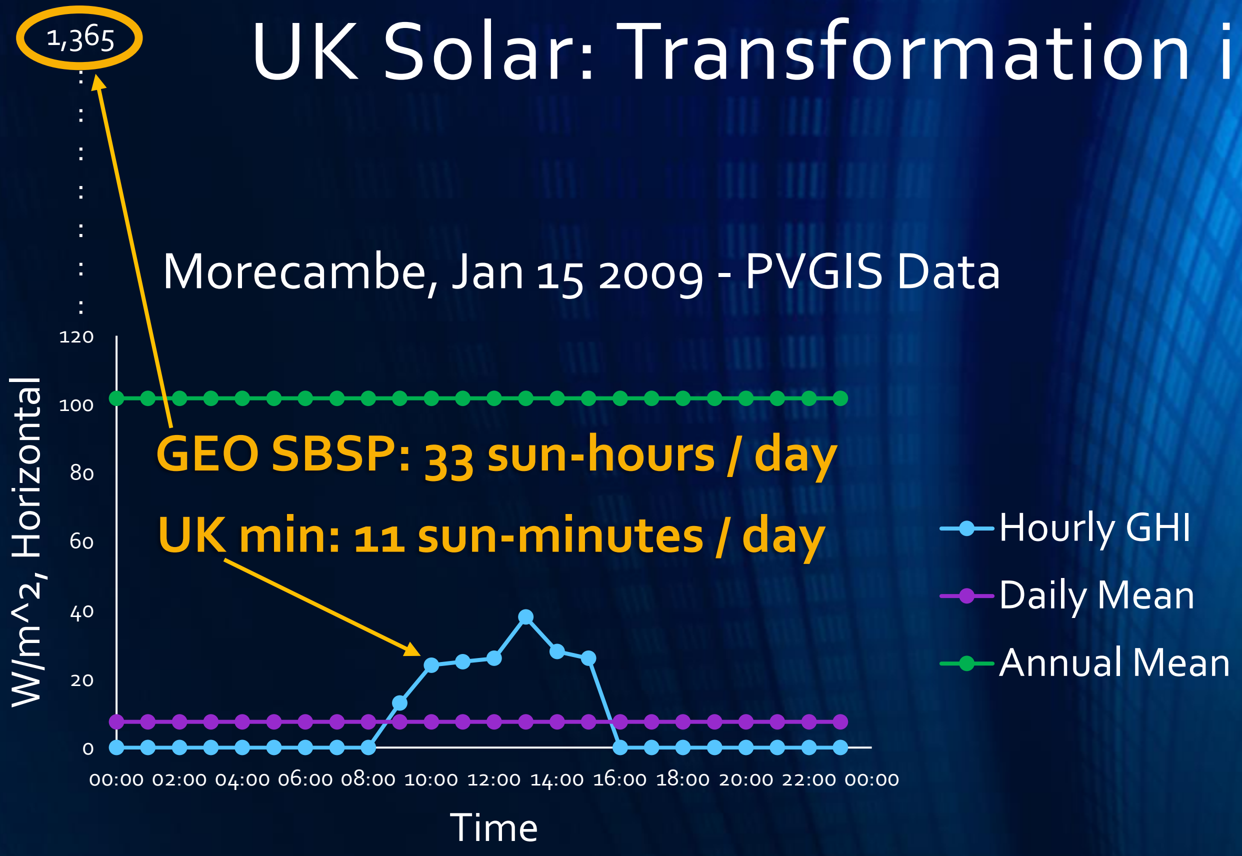
Wind Energy Storage:

- Li-Ion storage infeasible for multi-day durations
- Spare wind capacity could electrolyse/liquify H2
- Intermittent/inefficient use of capital equipment

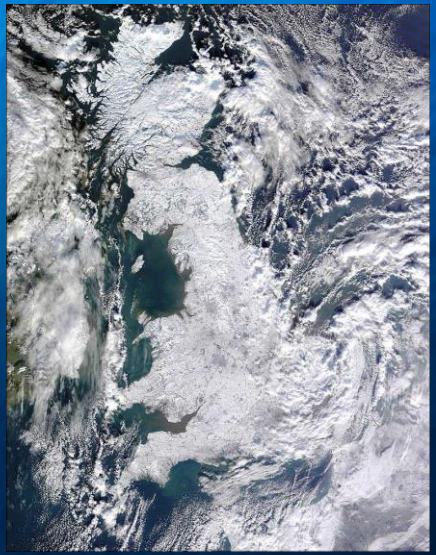
Space Solar:

- 10 times the surface electrical energy density of wind.
- Suitable as both dispatchable and exportable backup for wind

UK Solar: Transformation into Firm Baseload?



UK, Jan 9, 2010:



Without Seasonal Storage (per GW):

- Must cater for worst-case day: less than 1.6 W/m2 mean areal power density on Jan 15 2009
- **36 GWh** Li-ion storage = 133,000 tonnes (as cells alone), **USD 6.3 Billion***
- **630 km² PV** = 80,000 more than CASSIOPeiA CPV

*NREL 2040 median cost projection in 2018 dollars

With Seasonal Storage (per GW):

- **27 GWh** Li-ion storage = 100,000 tonnes (as cells alone), **USD 4.7 Billion**
- **58 km² PV** = 7,400 more than CASSIOPeiA CPV, 1.7 times greater area than a UK rectenna.
- 210,000 tonnes of green ammonia storage (UK grey ammonia production totalled 110,000 tonnes in 2022)

Why Not Distribute Power from Sun-Rich Regions?

IECL

- Morocco (Guelmim Oued Noun region) has 92 sun-days per year ✓
- Wind capacity factor is 52% ✓
- Politically stable, benefits also go to local community ✓
- Undersea HVDC cables, solar, wind and batteries are mature tech ✓
- £30 Million investment recently secured from UAE and Octopus Energy

	Xlinks		CASSIOPeiA
Initial Project Cost:	USD 21.9 B		USD 21.6 B
Mean Power to UK:	3.0 GW		2.0 GW
Subsequent Cost to 10 GW (estimate):	USD 43.8 B		USD 19.0 B
Total Cost:	**USD 65.7 B**		**USD 40.6 B**
Power Distribution Distance:	3,800 km	GEO - 54°N:	38,500 km
Basic Mass Breakdown (per gigawatt baseload)			
Copper:	96,000 tonne		208 tonne
Steel:	93,000 tonne	Silver:	7 tonne
Composite/Other:	61,000 tonne		785 tonne
Total Power Distribution Mass:	**250,000 tonne**		**1,000 tonne**

Does Space Have to be Expensive?

- Cost of space launch

Space Launch System
- USD 2B-4B per launch
- Circa 100 tonnes payload to LEO
- USD 30,000 per kg

SpaceX Falcon Heavy
- Mostly reusable
- USD 90M per launch
- Circa 64 tonnes payload to LEO
- USD 1,400 per kg

- Cost of space hardware

James Webb Telescope
- One-of-a-kind
- Hand-built
- Nano-metre precision

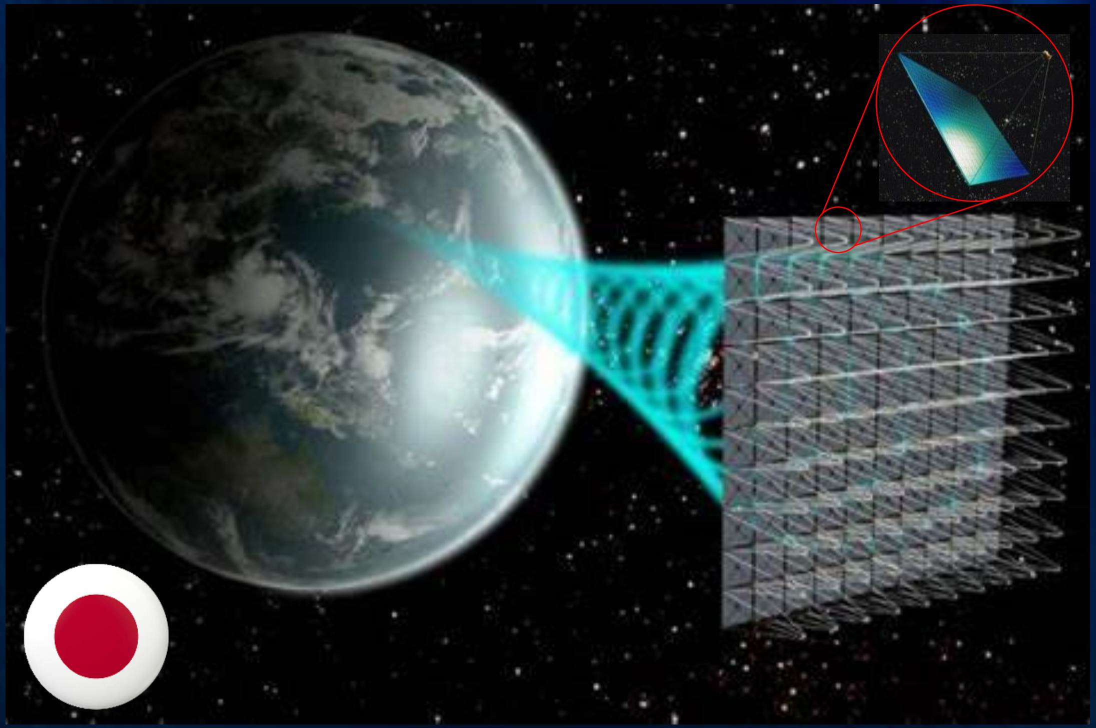
SpaceX Starlink
- More than 4,000 satellites produced
- Launched 60-at-a-time
- Dedicated factories and assembly lines

- Minimise size of SPS? → Constrained by diffraction physics
- Minimise mass of SPS? → Yes, maximise specific power


ECL
The Reusable Space Launch Revolution
ECL
[LEO payload launch costs]
$85,000/kg (1981)
$27,000/kg (1995)
$950/kg (2020)
$80/kg (20??)
< $100/kg (2040)
BLUE ORIGIN
SPACEX
21

SPS Concepts without Baseload (24/365) Capability

JAXA Tethered SPS – 2004-2023 (current)

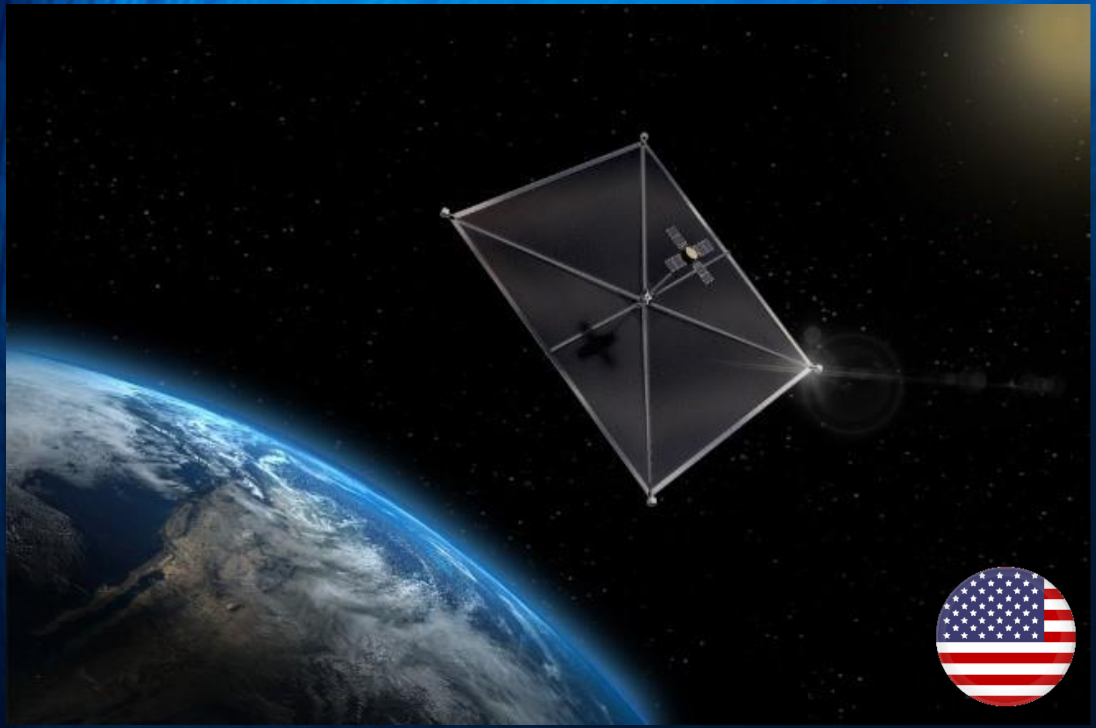


RF Phased Array always Earth-facing

PV on both sides of Sandwich Panel

Panel edge-on to Sun twice-per-orbit

CalTech SSPI / AFRL SSPIDR – 2013-2023 (current)



RF Phased Array at compromise-angle to Earth

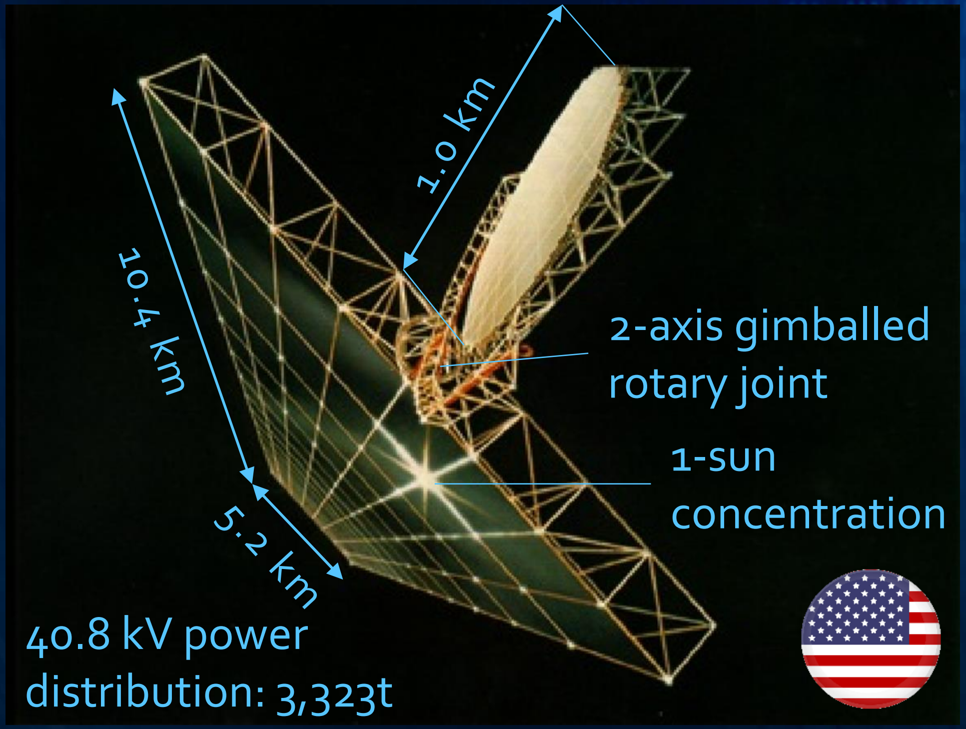
PV on one side of Sandwich Panel
(working towards both sides)

Panel edge-on to Sun twice-per-orbit

For baseload: both require significant battery storage - comparable to terrestrial solar

SPS Concepts with Power over Rotating Joints

NASA/DoE Reference System – 1977 - 1981

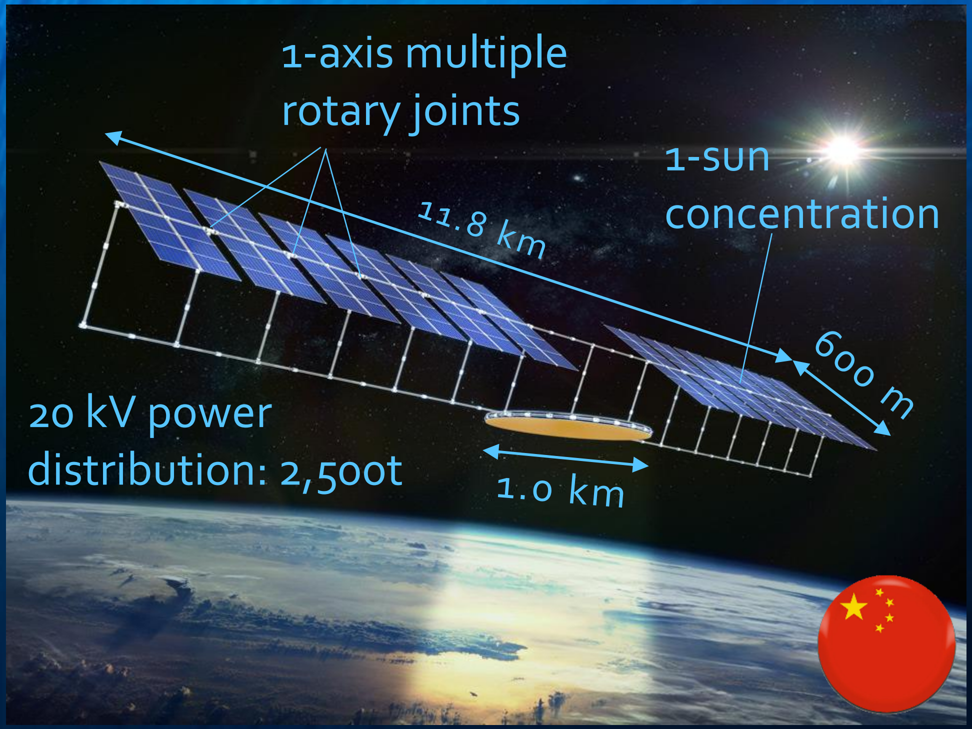


2.45 GHz, 5 GW delivered, 51,000 tonnes

➔ Specific Power = **98 kW per tonne**

A 2-sun concentration, 34,000 tonne variant also proposed ➔ **146 kW per tonne**

CAST MR-SPS – 2014 - 2022 (Current)



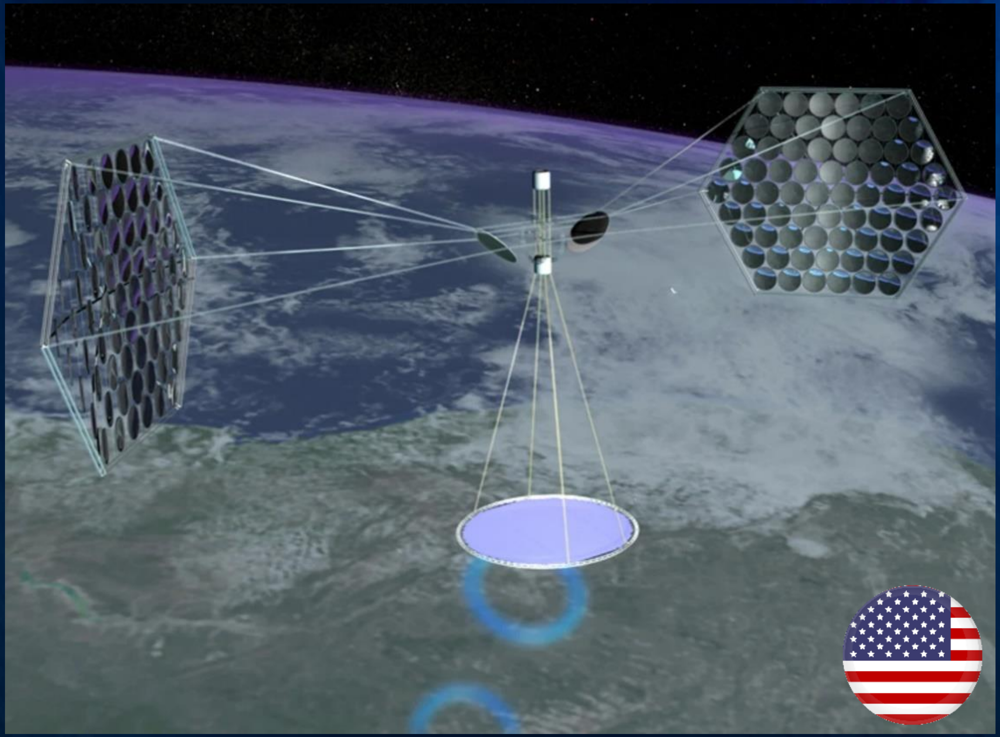
5.8 GHz, 1 GW delivered, 10,000 tonnes

0.3 GW wasted in 12 km distribution

➔ Specific Power = **100 kW per tonne**

Sandwich Panel Concepts with Articulated Solar Reflectors

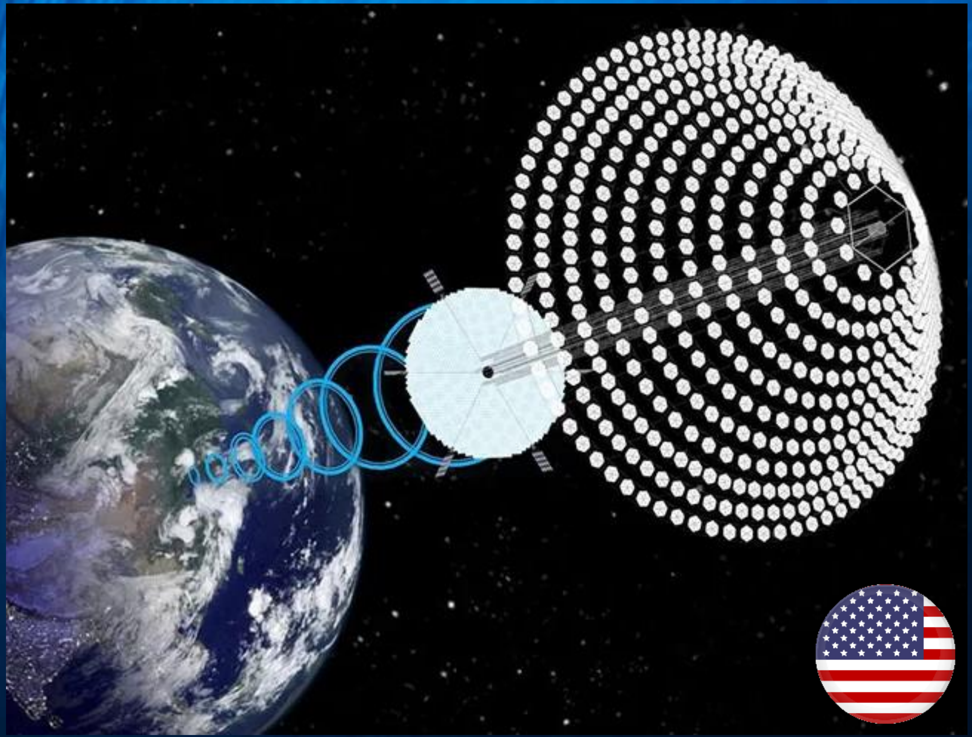
NSSO Modular Symmetrical Concentrator 2007



Primary concentrating reflectors on solar north-south axis rotate to follow the Sun throughout the orbit, with secondary reflectors redirecting sunlight to the PV at around 3-suns intensity.

The mechanical bearing is a failure risk.

JC Mankins SPS-ALPHA – 2011 - 2023 (current)



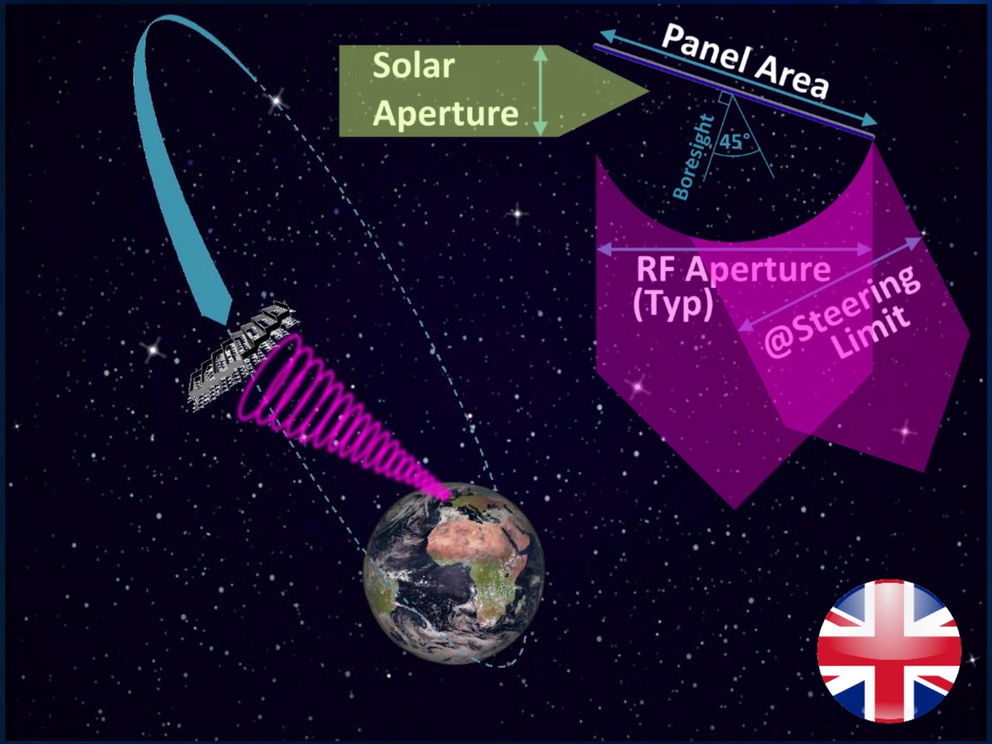
Multiple heliostatic reflectors on conical structure eliminate single points of failure

2.45 GHz, 2 GW delivered, 7,500 tonnes

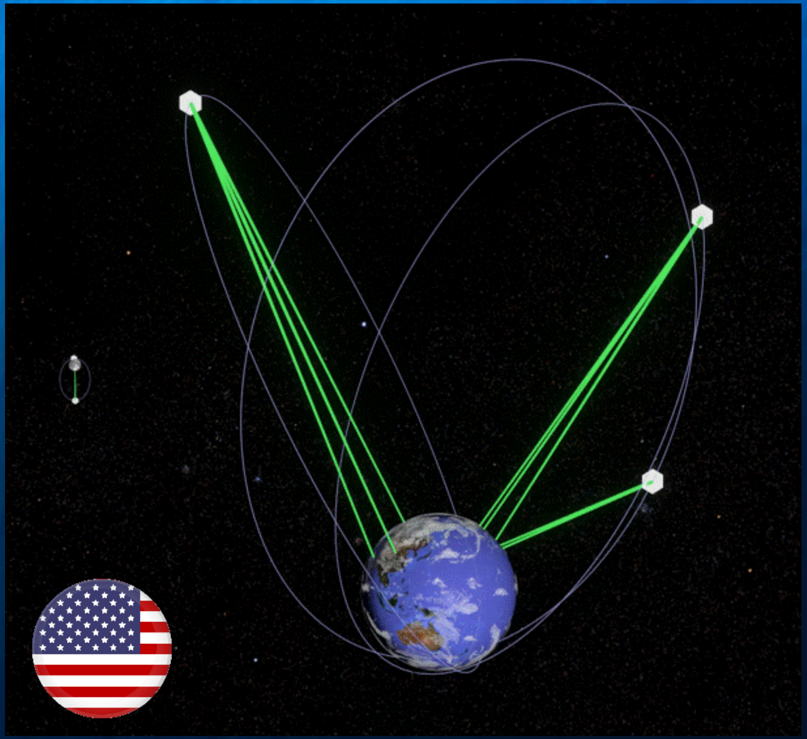
➔ Specific Power = **267 kW per tonne**

Solid-State Panel Concepts; Molniya Elliptical Orbit

Ian Cash - HESPeruS 2013 - 2016
(Highly Elliptical Solar Power Satellite)



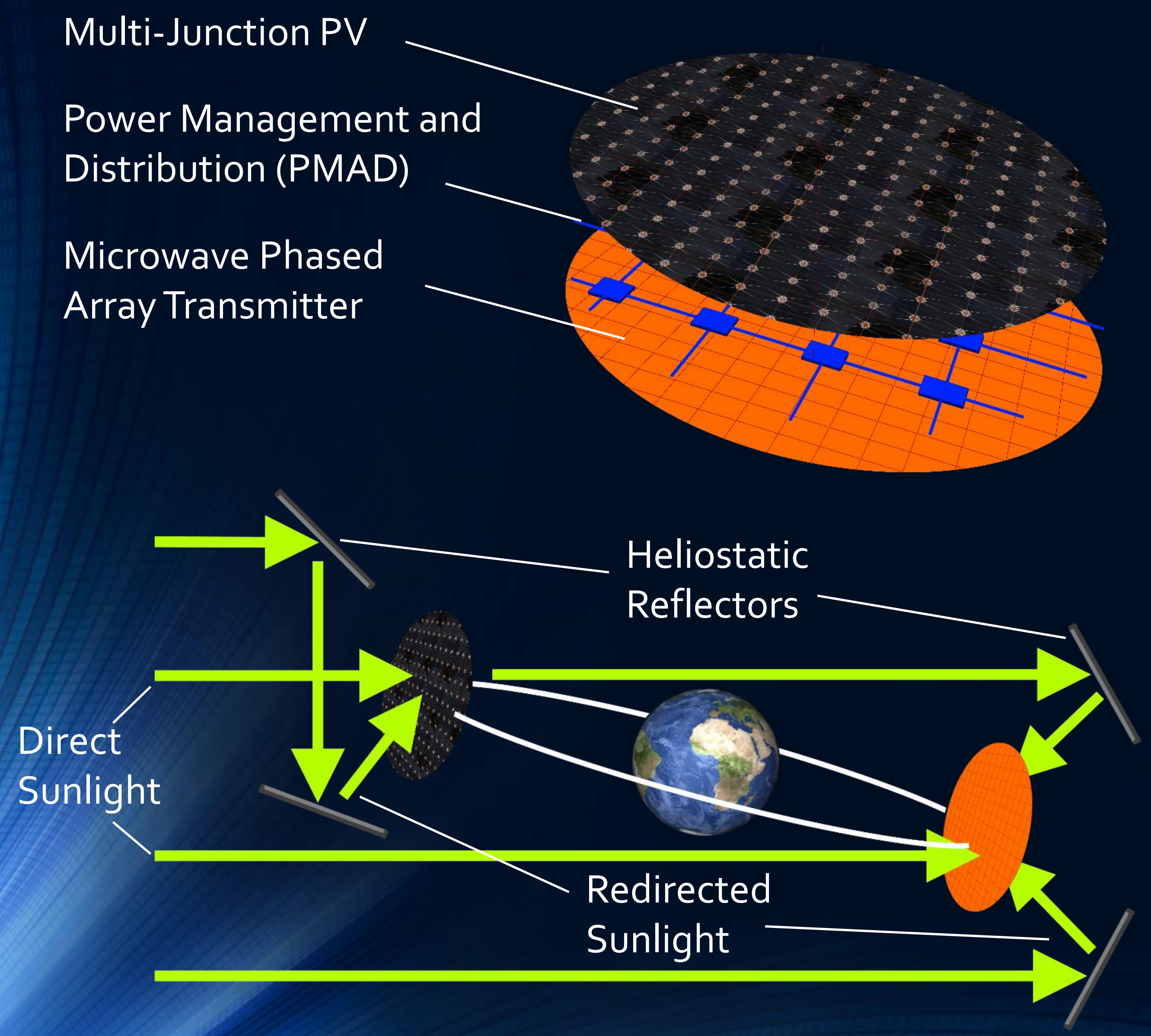
Virtus Solis 2019 - 2023 (current)



By choosing a Molniya elliptical orbit (12-hour period), a power satellite is taken high above the north pole where it loiters for an extended period; able to beam power to latitudes above 40° for around 8 hours of each orbit. With correct phasing, three solid-state satellites can deliver continuous power to two ground stations separated by approximately 180° longitude.

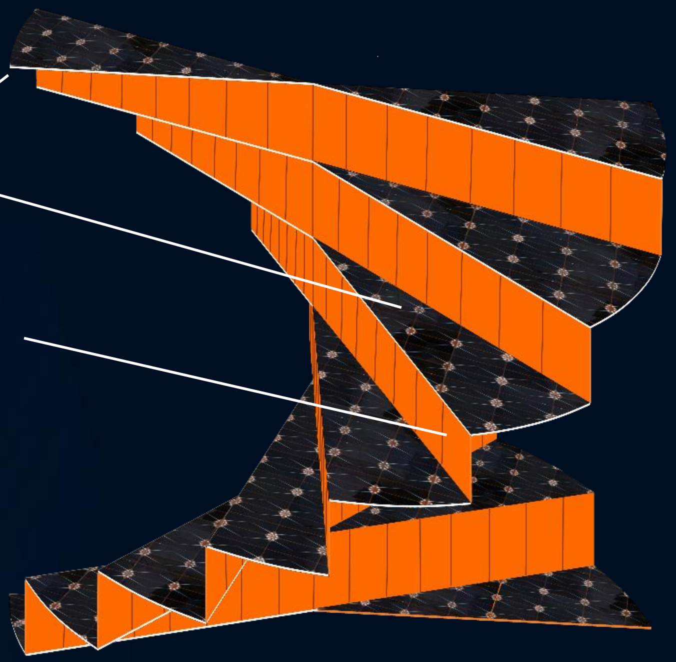
The challenge lies in choosing a compromise angle; trading solar aperture for RF aperture – which inevitably results in the panel illuminated at around 0.3-suns (circa 410 W/m^2) or less, offering poor specific power.

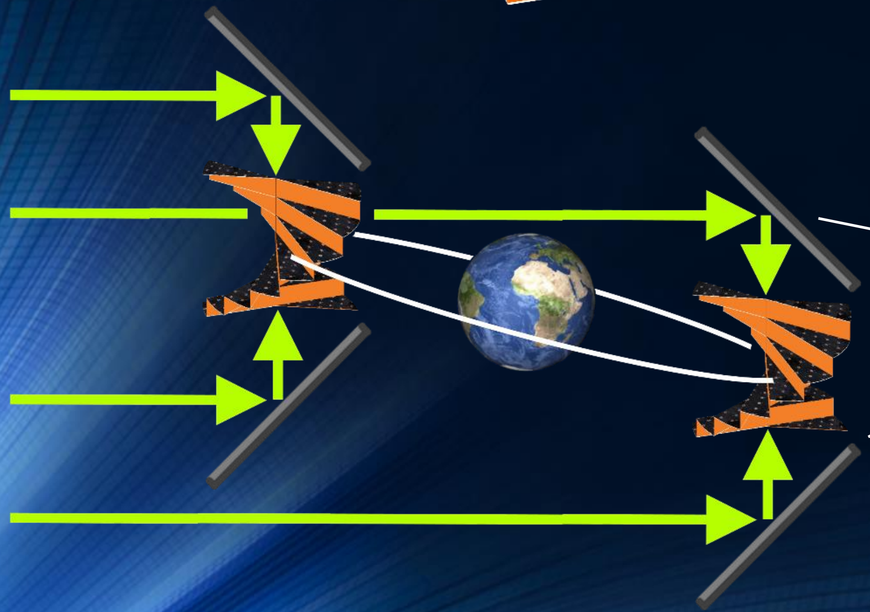
Sandwich Panel SPS Concepts



- PV and RF apertures matched; power distribution measured in mm and volts, not kilometres and kilovolts ✓
- Reduced mass through shared structure, elimination of electro-mechanical articulated joints ✓
- Solar concentration increases PV efficiency ✓
- Direct sunlight on transmit face is unwanted thermal load, limiting concentration to 3-suns approx. ✗
- Sunlight converges from wide, variable angle – preventing use of High Concentration PV (HCPV) ✗
- Earth-facing, high-inertia sandwich panel restricts to circular orbits ✗

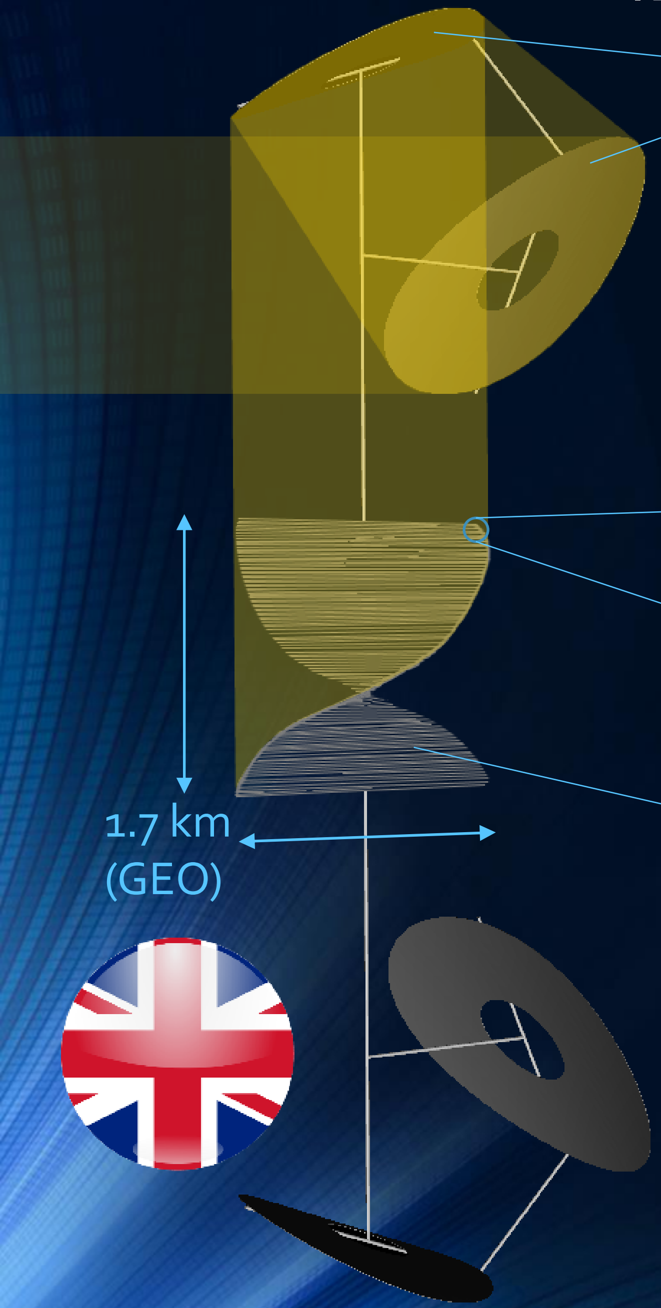
Highest Specific Power – CASSIOPeiA Array





- All the advantages of a Sandwich Panel ✓
- Further mass reduction through elimination of excess reflector area, heliostat bearings, motors, etc. ✓
- Doubled solar aperture increases power without additional structure ✓
- Minimal direct sunlight; 4-sun system concentration within thermal limits ✓
- Retained collimation enables power & efficiency gains of HCPV ✓
- Sun-facing, solid-state design circumvents momentum constraints for operation in all useful circular and Highly Elliptical Orbits (HEOs) ✓

IECL CASSIOPeiA (Mature) SPS Concept – 2016-2023 (current)

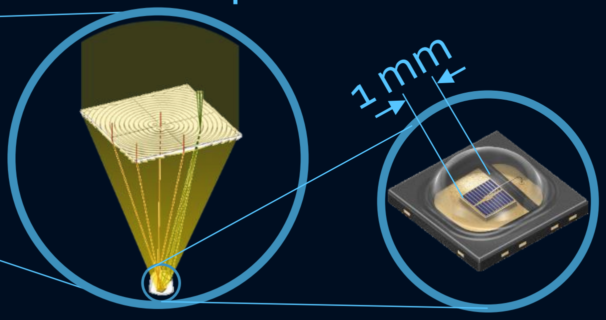


Solid-State Symmetrical Concentrator (patented)

- Conical surface curvature allows formation from flat film
- Collimation retained, allowing further concentration
- 2-sun concentration from solar north & south – 4-suns total

Microscale High-Concentration Photovoltaics (HCPV)

- CPV area (& rare elements) reduced by concentration factor
- PV efficiency increases, requiring only passive cooling
- Glass radiation protection increased, whilst mass reduced



Novel PV-Integrated Helical Phased Array (patented)

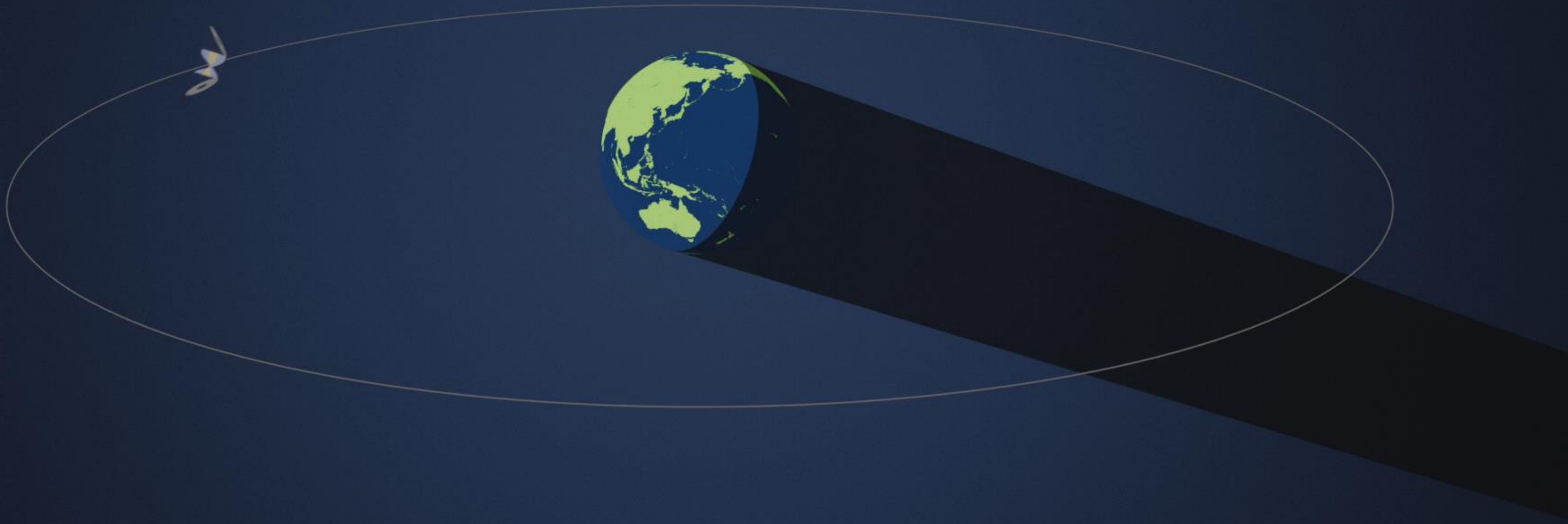
- Whole satellite remains Sun-facing
- Microwave beam steered through 360° during one orbit
- No temporal redundancy; all elements contribute to beam

Solar Photon-Pressure 3-Axis Attitude Control

- Additional reflector area (not shown) provides both passive and active attitude control via electrically-controlled variable reflection
- Propellent only required for station-keeping

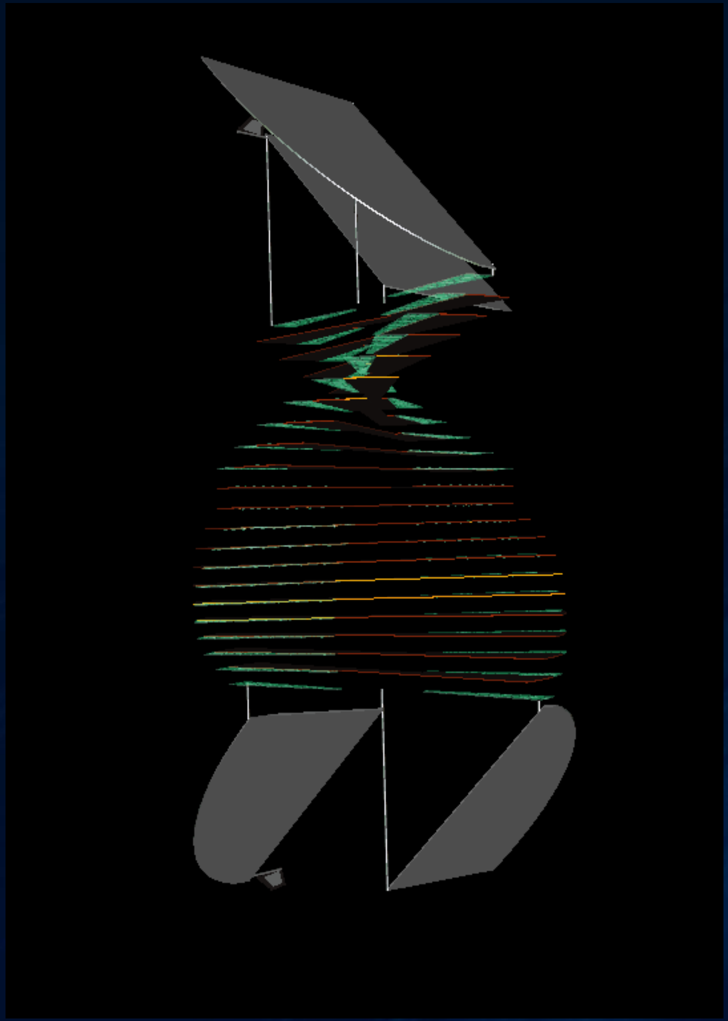
CASSIOPeiA Sun-Facing Attitude

*Not to scale

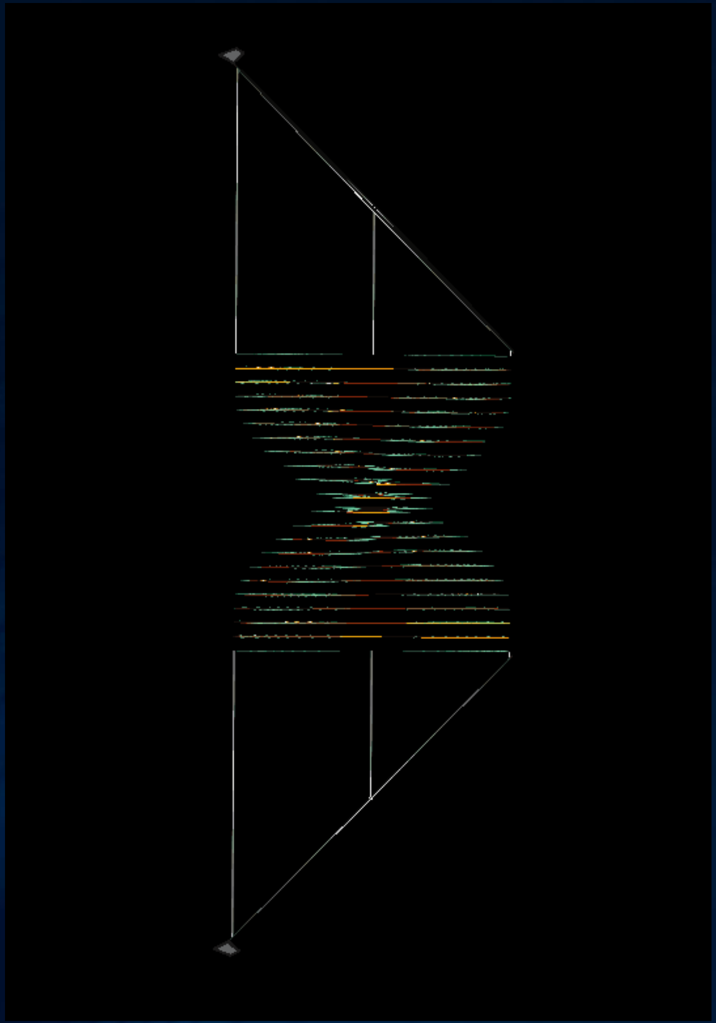


CASSIOPeiA SPS Reflector Variants

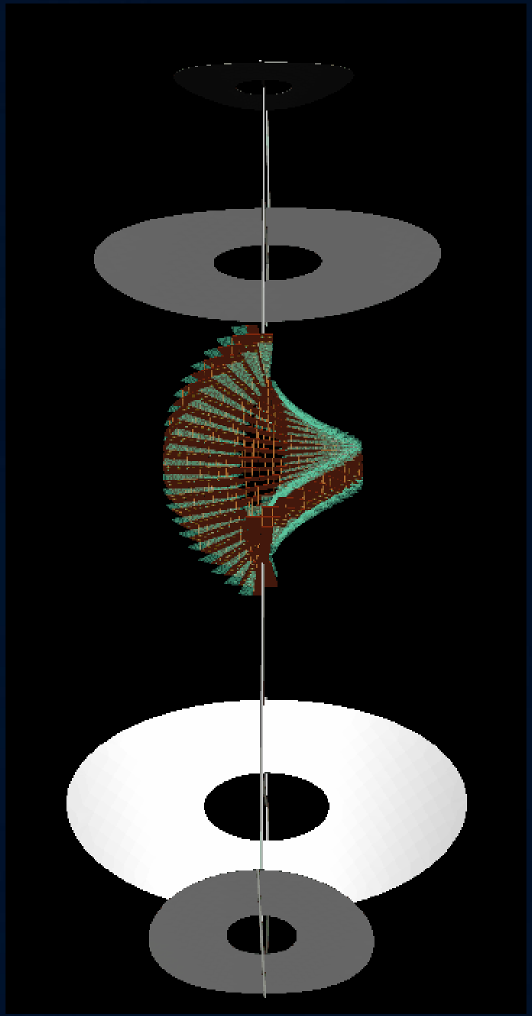
Planar Quadrant (1-sun)



Planar Full (2-sun)



SSSC (4-sun)



ECL

[SSSC: Solid-State Symmetrical Concentrator – GB2571383A pending]

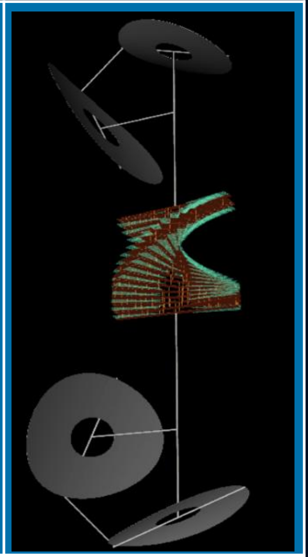
CASSIOPeiA SPS Variants & Power Scalability ✓

VARIANT

x4 Concentrator:

Highest specific power, approaching 1 MW per tonne.

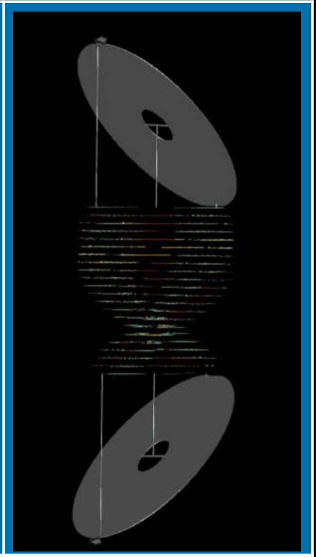
Best for highest power, lowest energy costs.



x2 Full Planar:

Good specific power, approaching 800 kW per tonne.

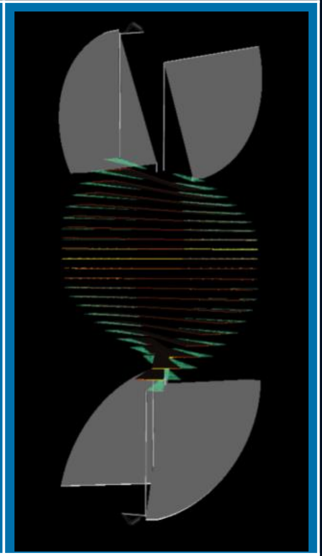
Optimises at medium power levels.



x1 Quad-Planar:

Lower specific power, approaching 660 kW per tonne.

Best for minimum mass, lowest capital costs.



Relative optimised delivered power for each variant from a particular orbit, at selected microwave frequency:

	x4 Concentrator	x2 Full Planar	x1 Quad-Planar
2.45 GHz	100%	72%	53%
5.8 GHz	42%	30%	22%

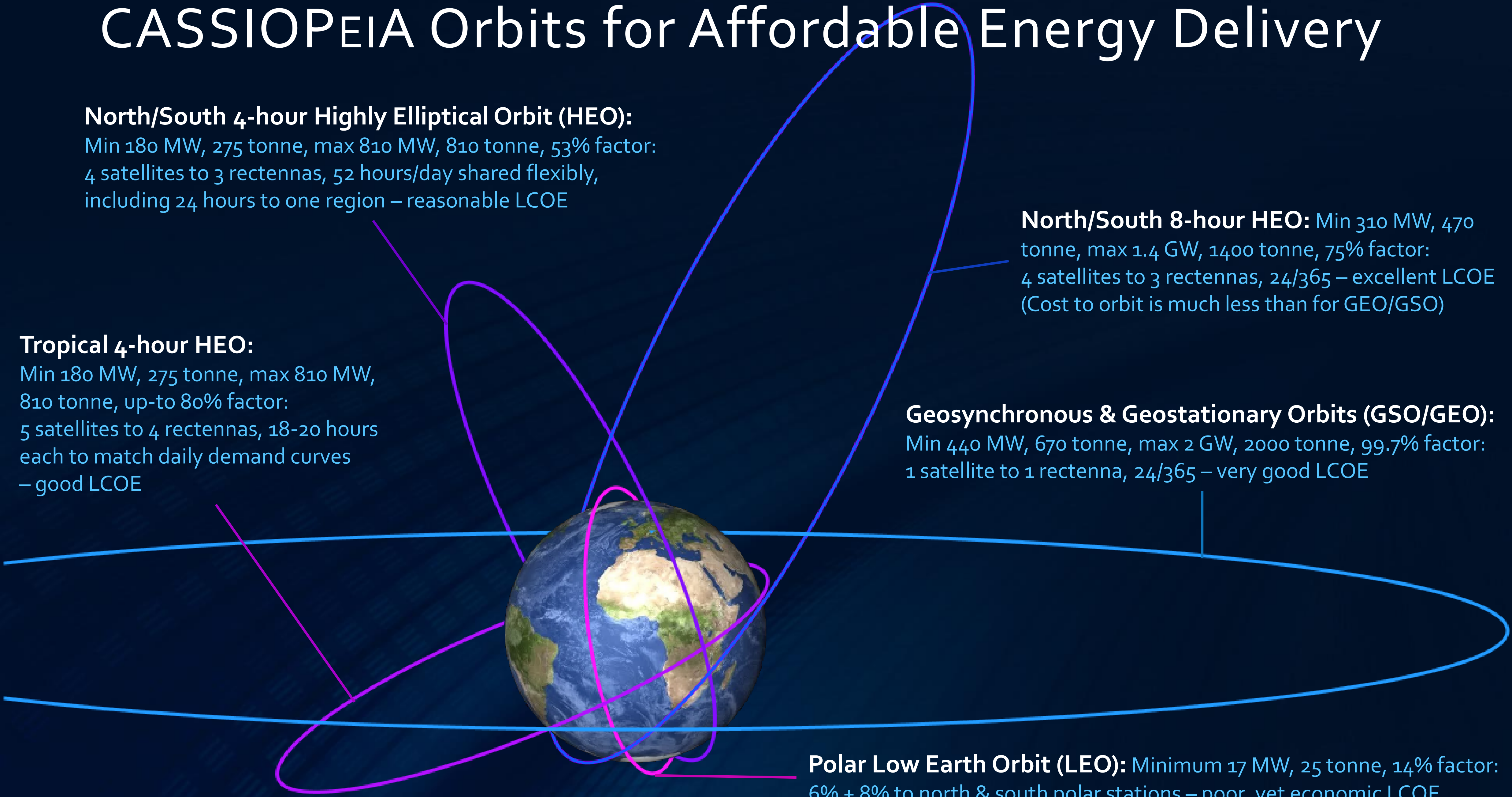
CASSIOPeiA Orbits for Affordable Energy Delivery

North/South 4-hour Highly Elliptical Orbit (HEO):
Min 180 MW, 275 tonne, max 810 MW, 810 tonne, 53% factor:
4 satellites to 3 rectennas, 52 hours/day shared flexibly, including 24 hours to one region – reasonable LCOE

North/South 8-hour HEO: Min 310 MW, 470 tonne, max 1.4 GW, 1400 tonne, 75% factor:
4 satellites to 3 rectennas, 24/365 – excellent LCOE
(Cost to orbit is much less than for GEO/GSO)

Tropical 4-hour HEO:
Min 180 MW, 275 tonne, max 810 MW, 810 tonne, up-to 80% factor:
5 satellites to 4 rectennas, 18-20 hours each to match daily demand curves – good LCOE

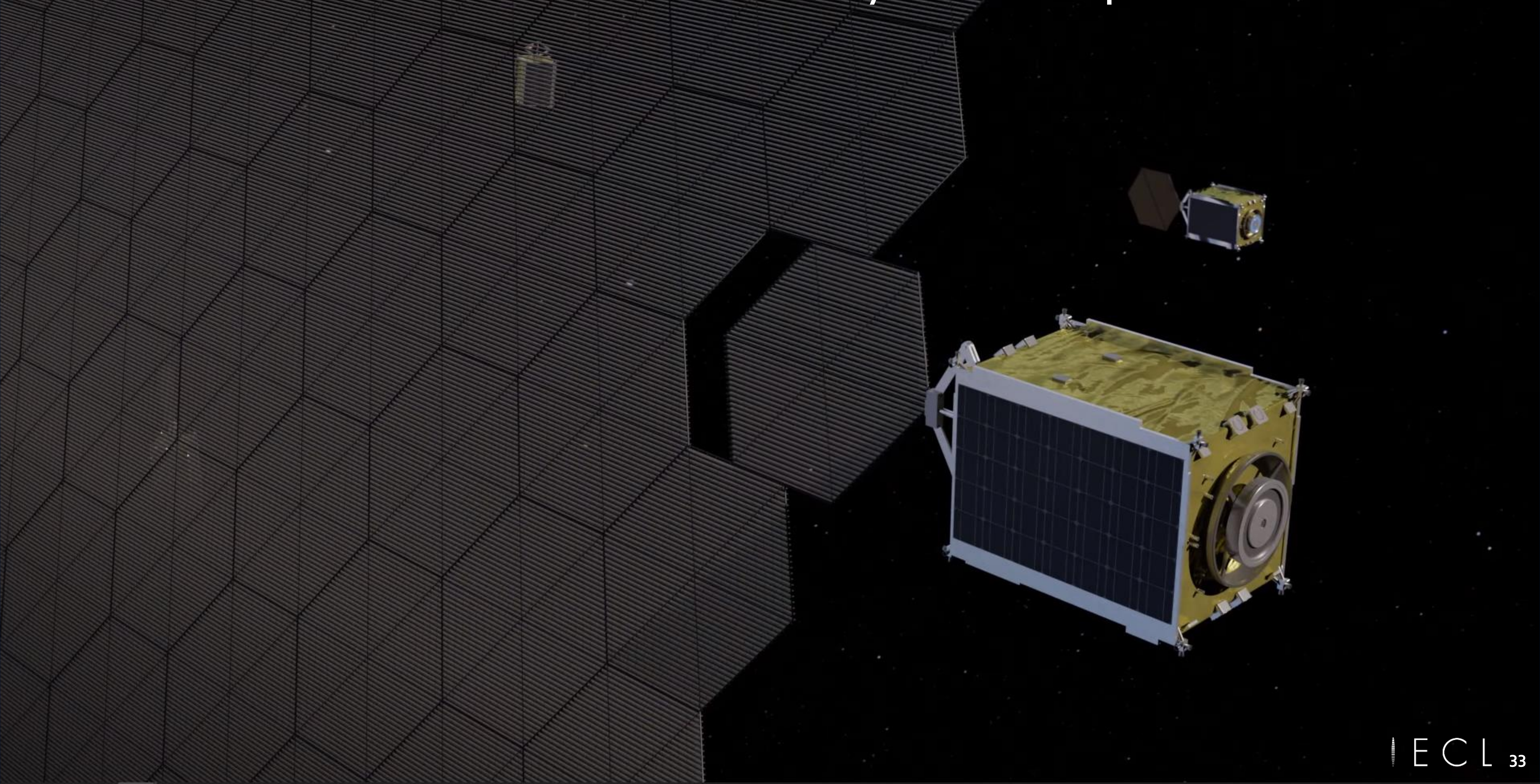
Geosynchronous & Geostationary Orbits (GSO/GEO):
Min 440 MW, 670 tonne, max 2 GW, 2000 tonne, 99.7% factor:
1 satellite to 1 rectenna, 24/365 – very good LCOE



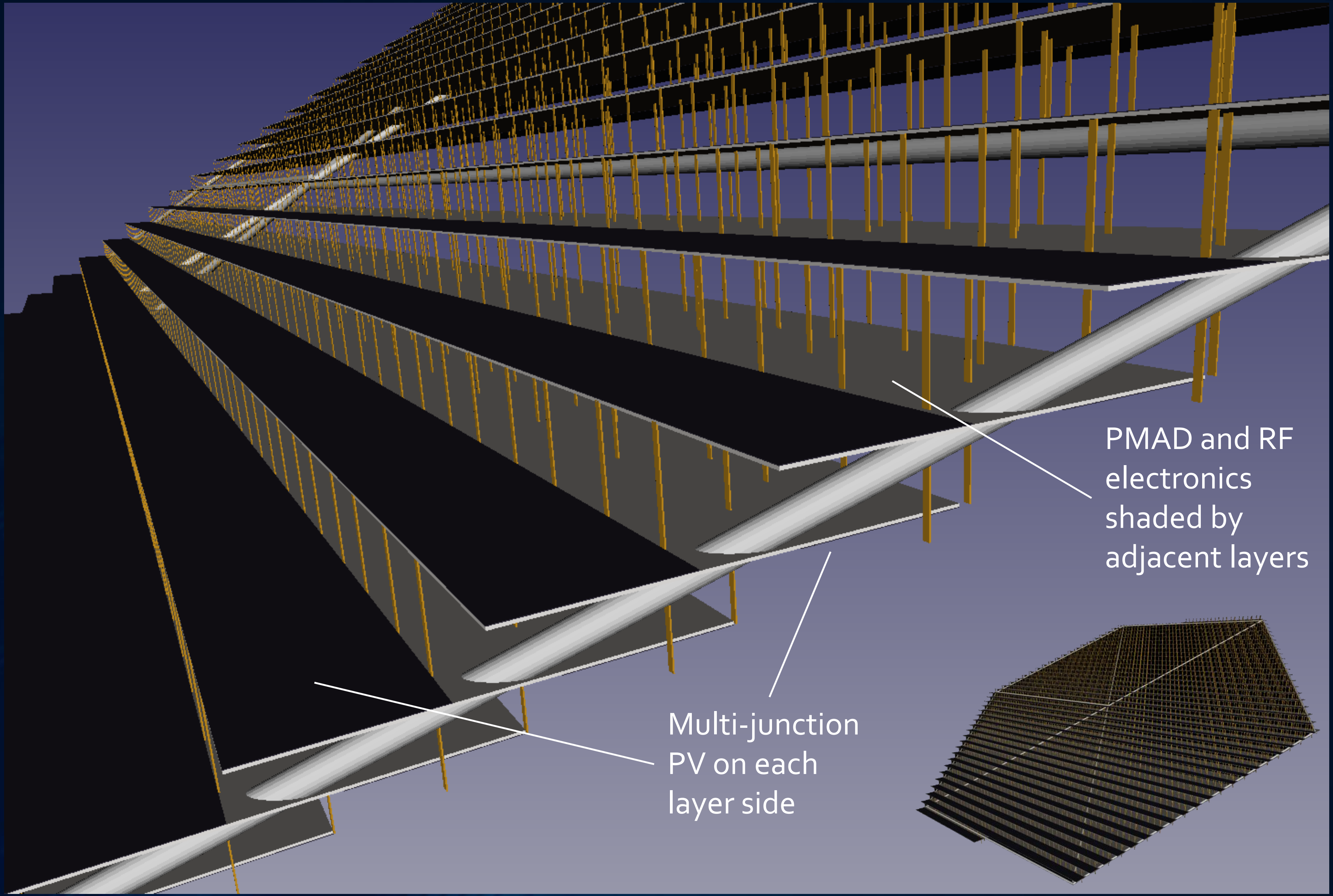
Polar Low Earth Orbit (LEO): Minimum 17 MW, 25 tonne, 14% factor:
6% + 8% to north & south polar stations – poor, yet economic LCOE

[Orbits are to scale]

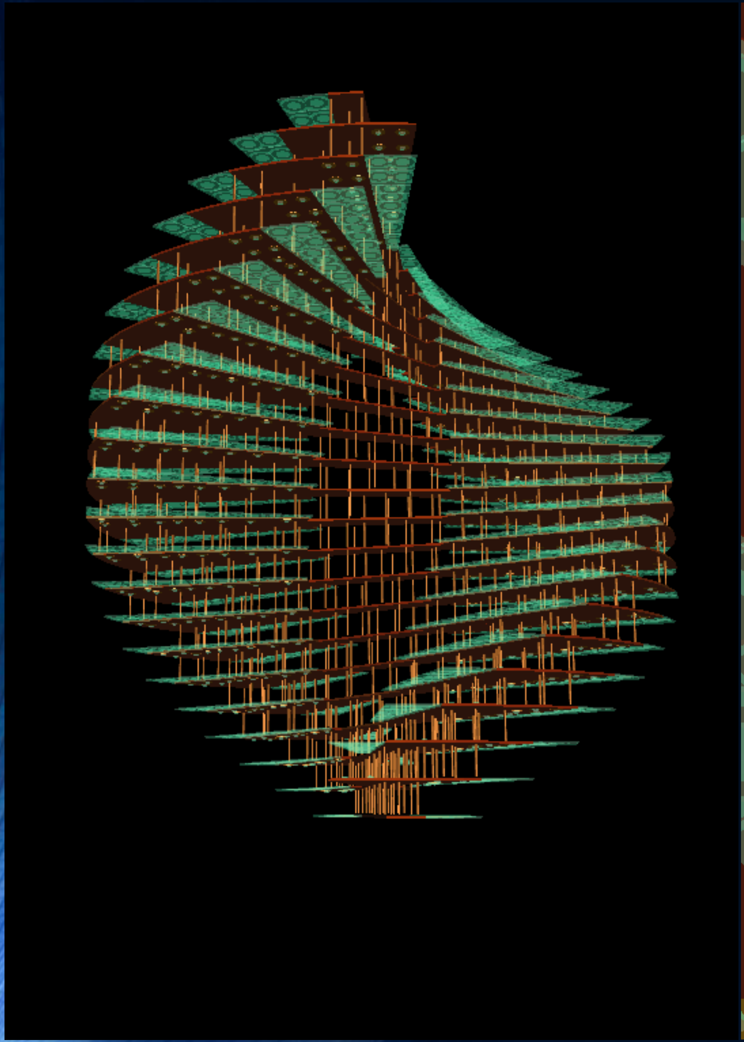
CASSIOPEIA Modular Assembly at Multiple Scales

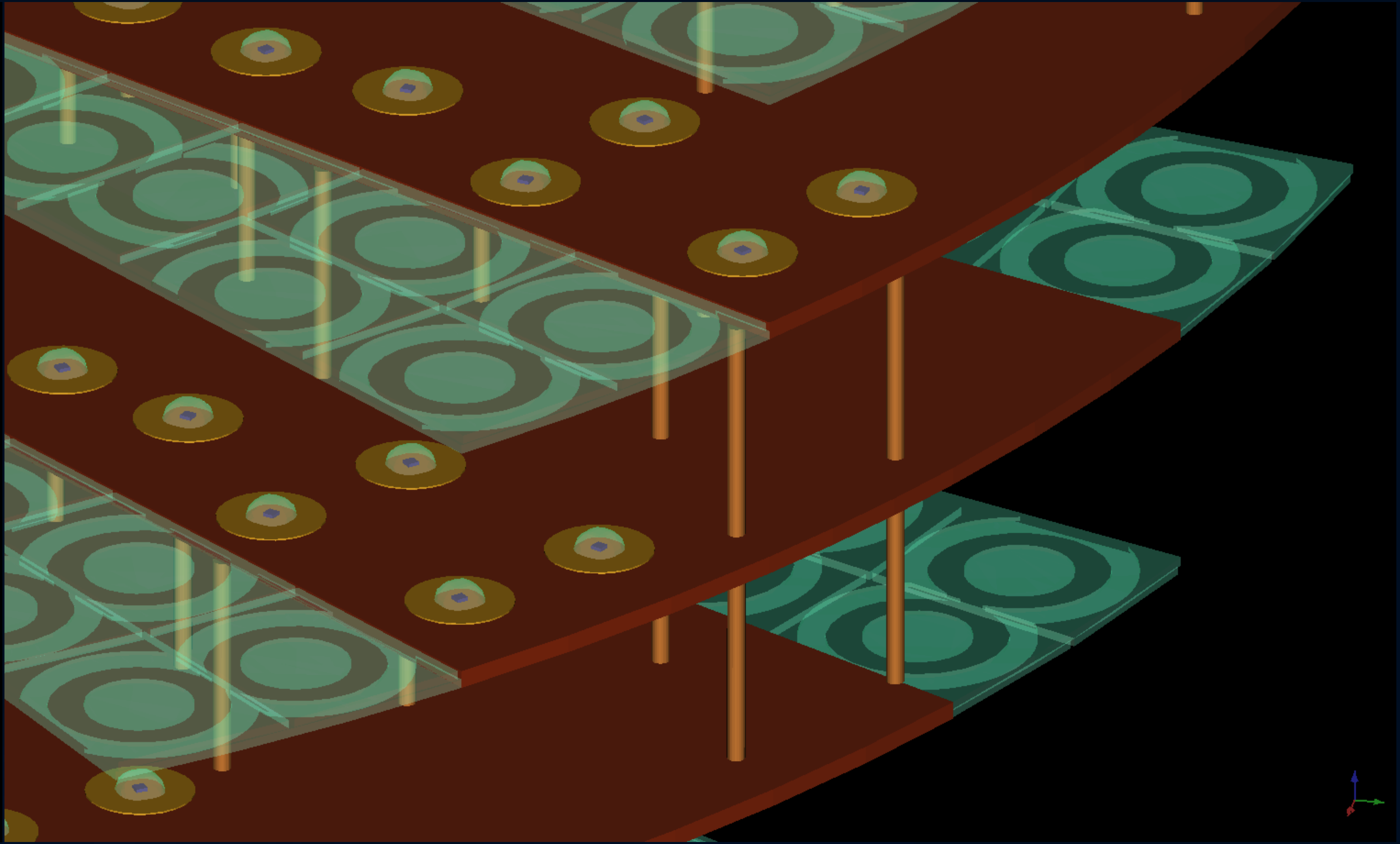


CASSIOPeiA Metre-Scale Module Close-up (PV Variant)



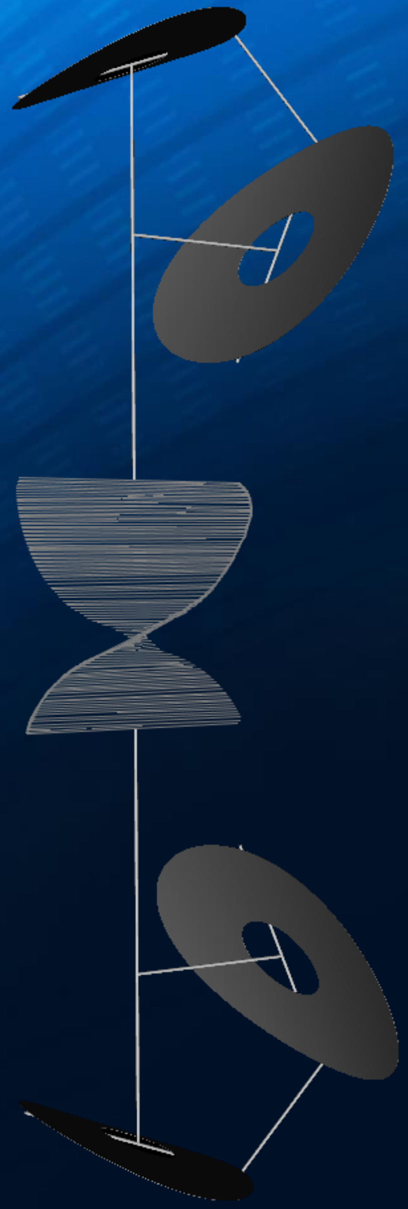
CASSIOPeiA Metre-Scale Module Close-up (HCPV Variant)





Requirements Met for Commercial Space Solar

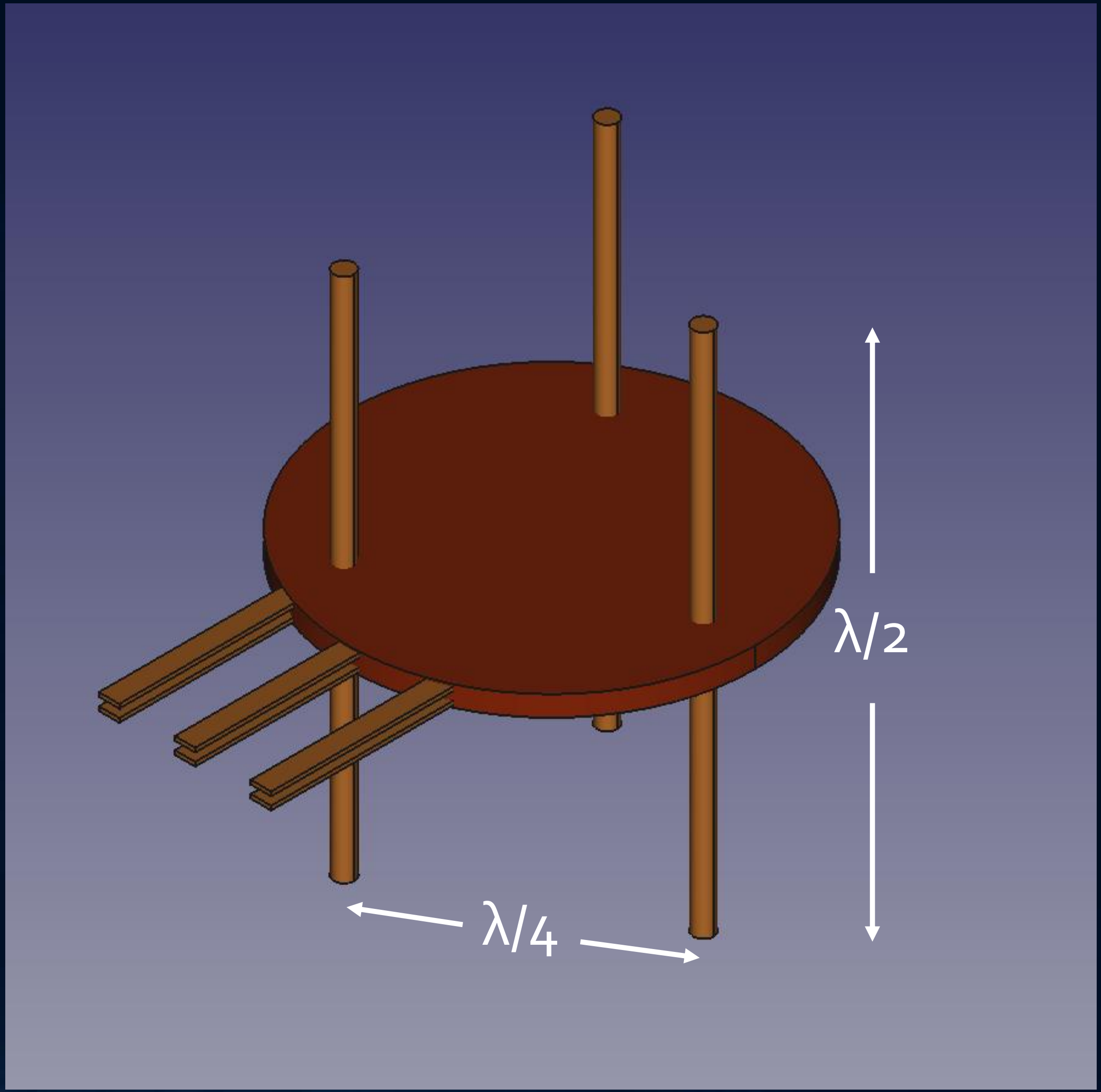
- Payload launch costs are already viable ✓
- Maximise Specific Power – 1 MW/tonne ✓
- Maximise Utilisation – 18 to 24 hours per day ✓
- Start smaller, not gigawatts – 180 MW ✓
- Modular assembly across multiple scales – small number of mass-produced module types ✓
- Operable in multiple orbits – including HEOs ✓



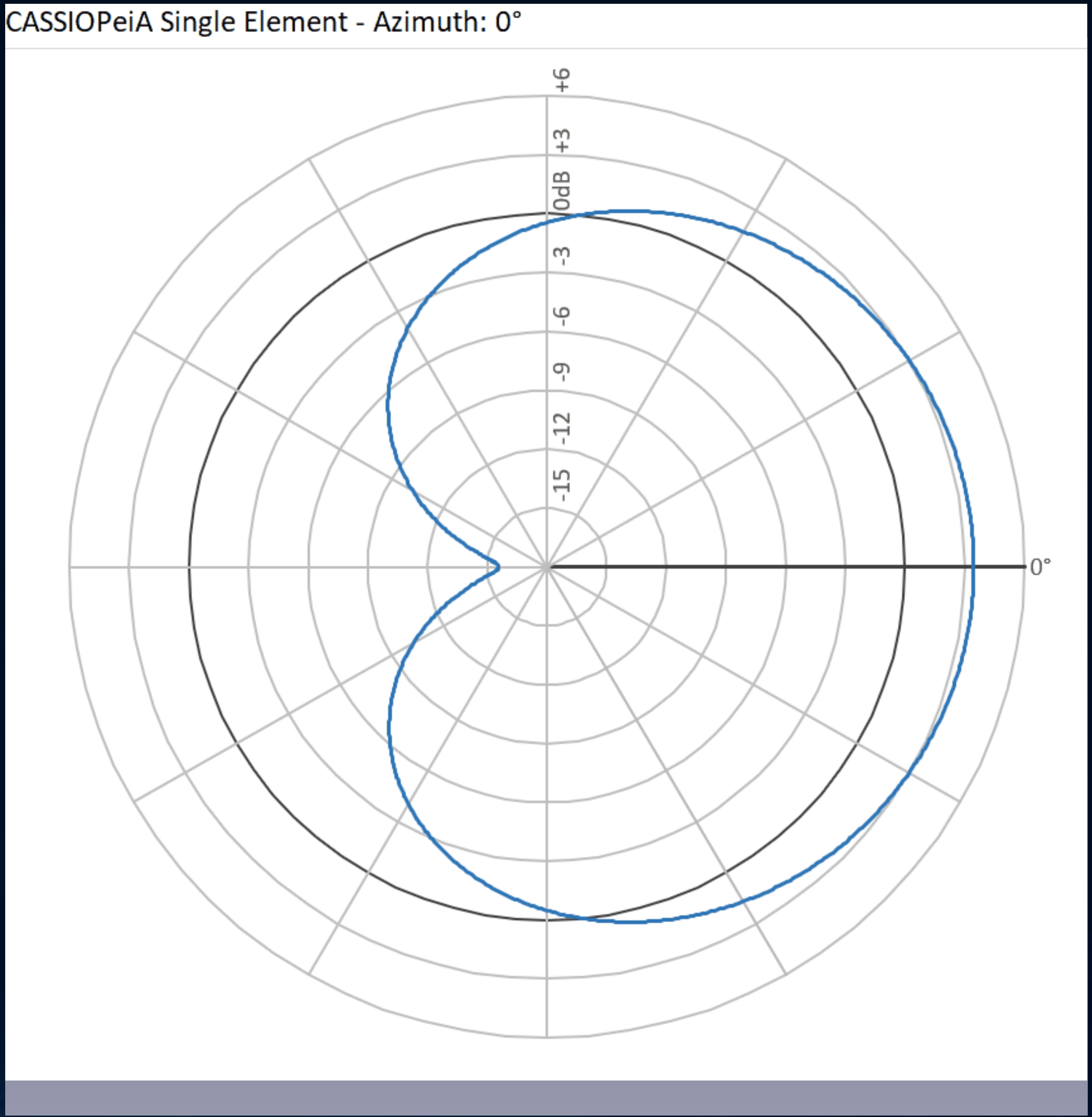
Questions?

Supplementary:

360° Steering at RF Element Scale



360° Steering at RF Element Scale

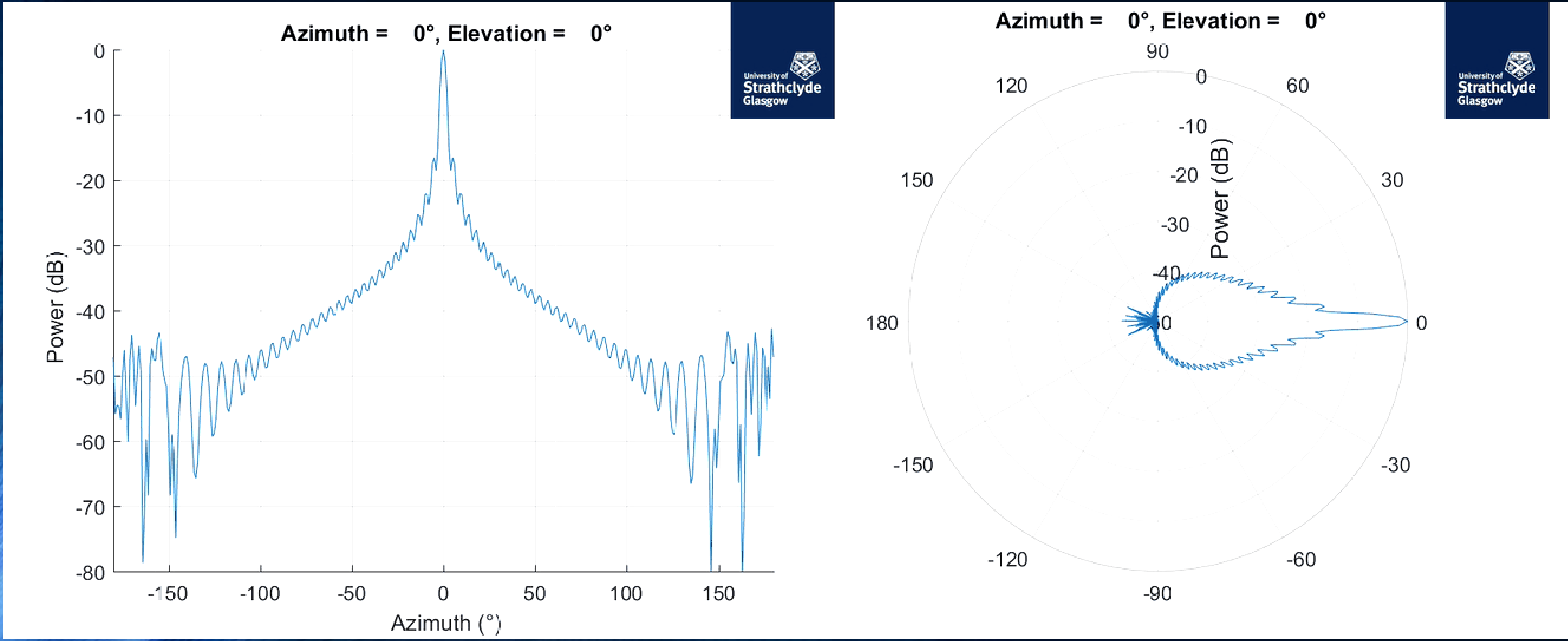


Cardioid Pattern:

Steerable null replaces the rear reflector (necessary with other phased array designs)

CASSIOPeiA Constant Aperture Phased Array

56x88 Elements – Independently Validated: U. Strathclyde, UK



CASSIOPeiA Constant Aperture Phased Array

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