PRE-PHASE A SYSTEM STUDY OF A COMMERCIAL-SCALE SPACE-BASED SOLAR POWER (SBSP) SYSTEM FOR TERRESTRIAL NEEDS

ESA – TALDA – TN2:

CRITICAL REVIEW OF DSR TECHNOLOGY

REPORT TO
EUROPEAN SPACE AGENCY (ESA)

July 17th, 2023 – Revision 2

ESA Contract No. 4000141171/23/NL/MGu.

NOTICE

This report was commissioned by the European Space Agency (ESA) on terms specifically limiting the liability of Arthur D. Little. Our conclusions are the results of the exercise of our best professional judgement, based in part upon materials and information provided to us. Use of this report by any third party for whatever purpose should not, and does not, absolve such third party from using due diligence in verifying the report's contents.

Any use which a third party makes of this document, or any reliance on it, or decisions to be made based on it, are the responsibility of such third party. Arthur D. Little accepts no duty of care or liability of any kind whatsoever to any such third party, and no responsibility for damages, if any, suffered by any third party as a result of decisions made, or not made, or actions taken, or not taken, based on this document.

TABLE OF CONTENTS

VERSIONING

Version	Date	Comment
ESA TALDA - TN2 - Technology Maturity.Revision1	24/05	
ESA TALDA - TN2 - Critical review of DSR Technology_PostSKR	20/06	Post SKR meeting: comments and correction added to Word
ESA TALDA - TN2 - Critical review of DSR Technology.Revision1.3	28/06	Added versioning tab Added techno assumptions described in RP 1-2-3 for solar pumped laser and reflecting mirrors
ESA TALDA - TN2 - Critical review of DSR Technology. Revision 2.1	17/7	Added non mature technology assessment + annex on optical systems analysis
ESA TALDA - TN2 – review technology_Revision 2.2	25/08	Added comments from ASR RIDs Name of file changed because too long for IT system

LIST OF TABLES

LIST OF FIGURES

I. LITERATURE REVIEW

INTRODUCTION

The use of orbiting mirrors to reflect sunlight to Earth for a multitude of interesting applications was originally described in 1929 by the German space pioneer Hermann Oberth in his book entitled "Ways to Spaceflight". These applications included the illumination of cities, melting of frozen waterways, and modifications to the weather and climate. Professor Oberth was not content with just proposing the idea; he also went into considerable detail to support it mathematically and to show how it could be implemented.

However, Oberth was so far ahead of his time that the technology was not available in 1929 to implement his advanced concepts. The next thorough treatment of orbiting solar reflectors was presented about 38 years later by A. G. Buckingham.

Buckingham's early efforts were primarily concerned with illumination from space for both civil and military applications. Much of the work was released in 1967 and 1968 in papers written by Buckingham and H. M. Watson. During this time period, solar reflectors were studied for use in the war in Vietnam by several companies. The technology existed for fabricating and launching the reflector sizes under consideration (approximately 75 m in diameter), but even with the advocacy of NASA and the Air Force the project was cancelled, primarily because of an anticipated early end of the war.

A more comprehensive treatment of orbiting solar reflectors, their missions, and applications has been by Krafft A. Ehricke, a renowned engineer responsible for many of this country's space age developments. Dr. Ehricke published papers on "space light" from 1970. His studies cover the broad spectrum of potential applications including illumination, increased plant yield by enhancing photosynthesis, electric power generation, and climate control.

The most intensive studies of solar reflectors for the production of electrical energy were conducted by Kenneth W. Billman and associates at the NASA Ames Research genter from 1976 to 1979, in a study program designated SOLARES. The results of these studies indicated that the SOLARES baseline concept, which used 80 000 of 1-km orbiting reflectors that could generate 220 GW of electricity. These studies were terminated in 1979 at the Ames Research Center. The NASA Langley Research Center took over from 1977 to 1981 to better define solar-reflector applications pertinent mainly to energy production and illumination from space. A 1982 NASA Technical Paper[1] which gathers a synthesis of physical equations to be taken into account was issued in 1982 to presents the findings of these studies, of but it is limited to only those concerning illumination from space. Its table of content is provided in annex in order to show the covered topics

Along with deployment of photovoltaic solar farms from the late 2000s, other studies of orbiting solar reflectors have focused on applications for terrestrial solar power enhancement. Some envisaged a constellation of 18 reflectors (each comprising a 10 km diameter array of individual 1 km reflectors) in a 1000 km polar orbit servicing some 40 solar power plants during dawn and dusk.

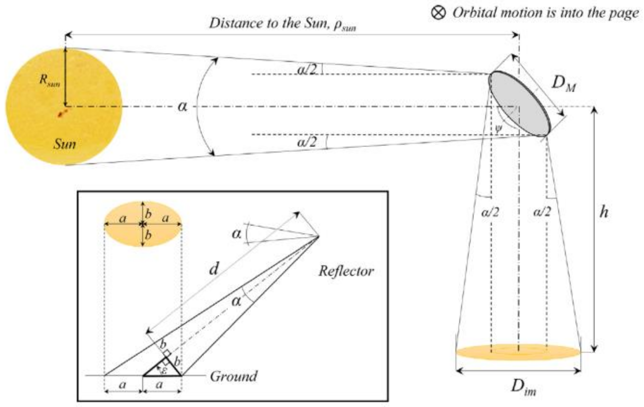
In parallel, the concept of energy transport by radiofrequency beam is patented by Peter Glaser in 1973 and matures up to today.

[1] NASA Technical Paper 2065 “Illumination From Space With Orbiting Solar-Reflector Spacecraft” by John E. Canady, Jr and John L. Allen, Jr, dated September 1982

WHY DID PREVIOUS DIRECT SUN REFLECTION STUDIES NOT MATERIALIZE IN PROJECTS?

One reason is law of physics, others are a matter of maturation of technologies in space and on ground, and the last is geopolitical:

THE MINIMAL SIZE OF ILLUMINATED SPOT ON THE GROUND



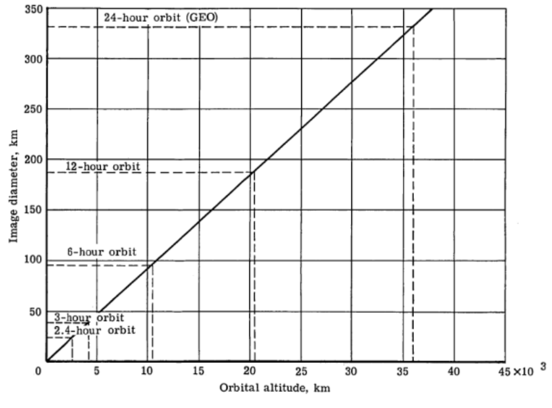


Figure 5.- Image size plotted against orbit altitude.

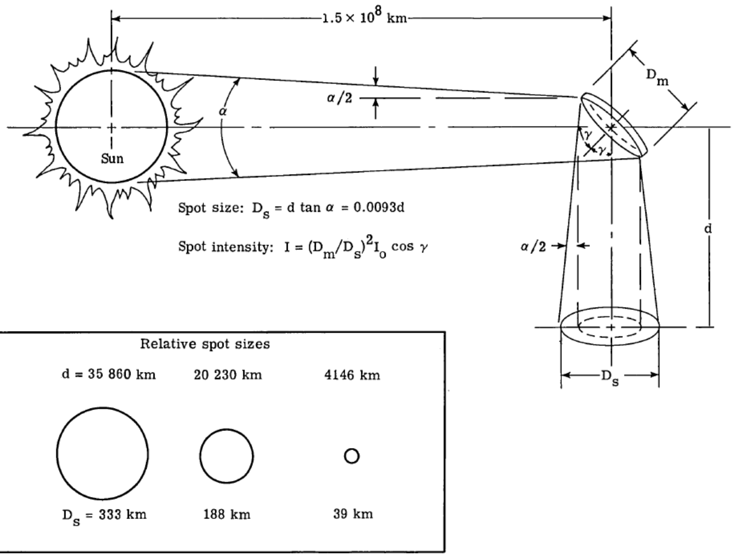


Figure 4.- Geometry for ideal mirror optics. α = 0°31'59.26";
I_o = 136 700 lux.

The sun is huge, even 150 million km away its size generates a very large spot-on ground from a flat mirror placed thousands of km away.
It was not a concern, a century ago, when foreseen applications were illumination of cities or heating of frozen area.
But power delivery cannot come with cancellation of the night for millions of citizens around.

THE COMPLEXITY OF HUGE ASSEMBLY IN SPACE

Assembly of a monolithic flat mirror of several km^2 is out of current state of art.
In addition, it is very complex to manage its attitude in front of all the applied forces (solar pressure, space weather, gyroscopic torques, inertia, drag, gravity gradient …).

It is very challenging to repoint it constantly with accuracy. It is very challenging to shape accurately its flatness or concavity.

Such a huge assembly is fragile in front of debris collision, is not easy to maintain, to repair or to upgrade.

THE LOW COMPETITIVENESS OF PHOTOVOLTAIC SOLAR ENERGY BEFORE 2010

During decades, the PV solar energy was convenient only for small applications in remote area, far from electric grid, but was not competitive for large power plants.
It is with the pressure of the global warming, thanks also to technological improvement, that solar farms started to take place in the energy mix, connected to the grid altogether with other renewable energy.
Today hundreds of billion dollars are invested in solar farms around the world.

THE LOOK FOR LOCAL SUPPLY OF ENERGY

Because space can deliver everywhere on Earth, the natural aim for space-based solar power is to deliver directly next to the end user, just like all the other space applications.
Because direct sun reflection power cannot be delivered without light, it cannot feed the local need in electricity of end-users in inhabited area, like European citizen. But electricity is only 20% of European energy consumption.

In the same time, the same European citizen are locally feed, at 80%, by fossil energy that is transported to them (and that is generating CO2 in European air, wherever the fossil energy comes from)

THE BREAKING EVENT

The HydroCarbon Rich Countries are preparing a switch towards hydrogen they can produce from sun and export like oil and gas. Even if they start with 20% conversion to hydrogen and derivative, the corresponding amount of energy is several times more than current European supply in electricity. And they will supply Europe with those green fuels for the good sake of all.

Their solar farms are sized in tens of km2, most of them are in uninhabited area where permanent sun light is not a problem. They are directly compatible with additional sun light.

Actual experience of swarm of autonomous drones could allow to brake down the huge structure in much smaller satellites that fly in swarm to form a parabolic surface that can focus to much smaller spot on Earth.

II. STATE OF THE ART

MAJOR TECHNOLOGIES OF DSR

- Attitude control
- On-orbit management, power and distribution
- Thermal control
- Solar power
- Pointing system
- Structure (light metallic alloy, inflatable, …)
- Mirror (optical accuracy, light weight, unfoldability, durability, etc.)
- On-orbit additive manufacturing
- Other advanced technologies (solar pumped laser, AI, …)

Three technical challenges for space reflectors:

- ***Maintaining shape*** flatness or concavity with sufficient accuracy
- ***Attitude control*** in front of all the applied forces (solar pressure, space weather, gyroscopic torques, inertia, drag, gravity gradient …)
- ***Repointing*** constantly with sufficient speed and accuracy

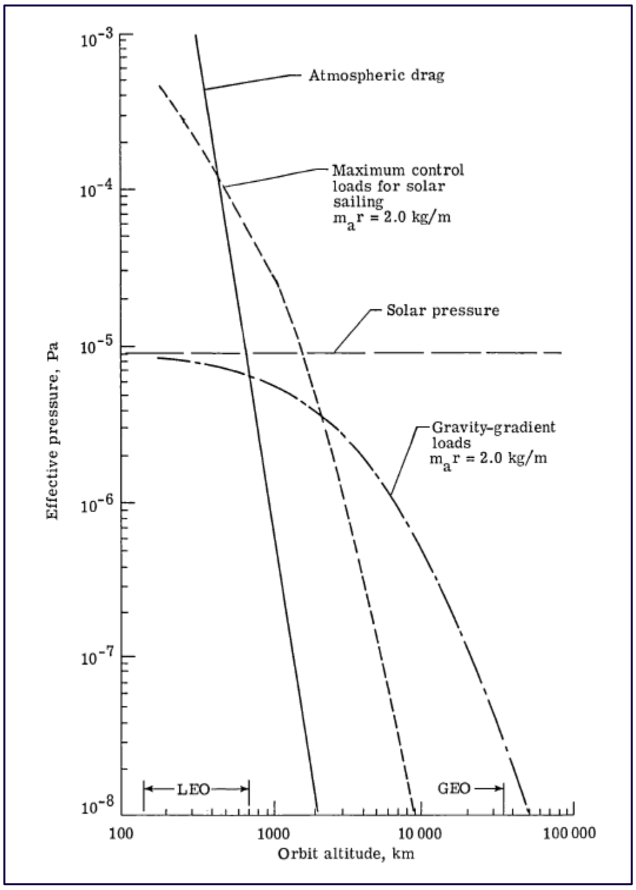


Figure 1: Maximum loads on reflective membrane of a 1 km spacecraft at different orbit altitude. Source: Dassault Aviation

CONFIGURATION OF DSR

- **Unique element** put into orbit like a satellite with a deployment of the reflector inspired by the giant antennas of the NSA (Magnum, Jeroboam, etc.). Popular solution.

- **Constellation** of large and/or small mirrors

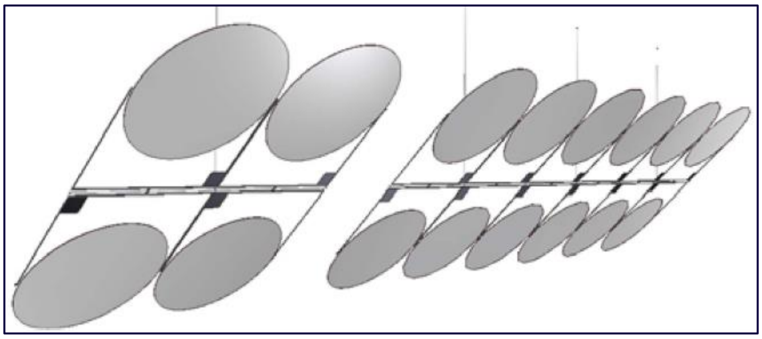


Figure 2: Each MiraSolar satellite can be built ip from multiple mirror segments. Four hundred segments in a linear sequence will produce a 10km diameter 1 kW/m² sun beam.
Source: Dassault Aviation

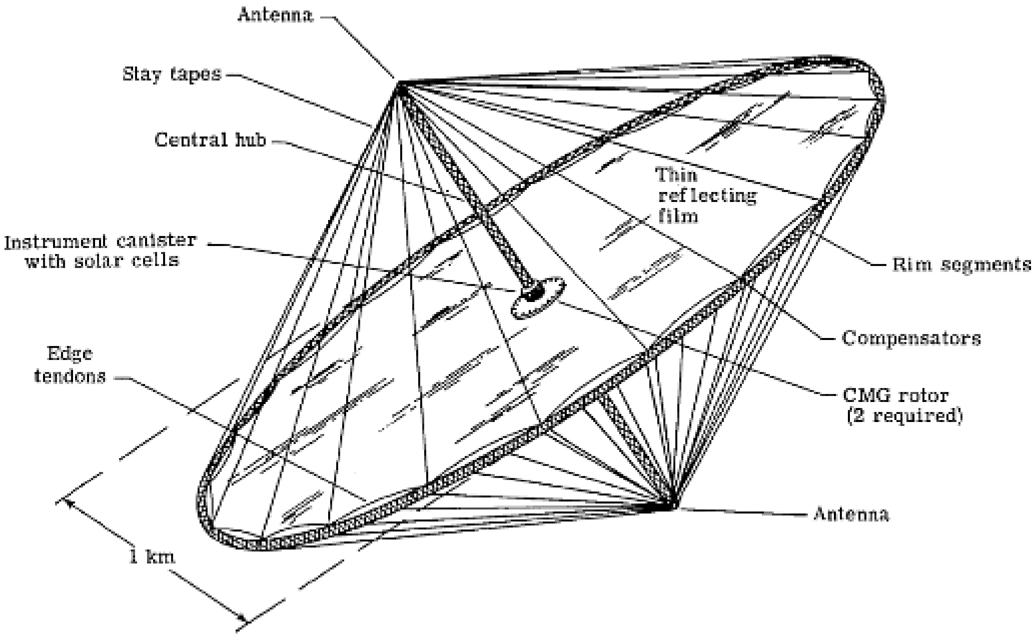


Figure 3: NASA project of 1982

DSR APPLICATIONS

For a century, studies of space solar reflectors have proposed the following applications:
Energy (the majority of applications studied);

- Agriculture (USA/Ehricke);
- Lighting of Arctic areas: Soviet and American studies (Nasa for lighting of Alaska);
- Lighting of theaters of military operations (priority at the time of the USSR and for the Vietnam War in the USA);
- Lighting for “emergency situations” like floods, earthquakes, … (Nasa);
- Illumination of the Panama Canal (Nasa);
- Lighting of sensitive areas (borders, etc.);
- Illumination of space sites in LEO;
- Geoengineering (USA: climate modification and enhancement of photosynthesis);
- Lighting of celestial bodies (Moon and Mars).

Today, the most promising of application is lightning of solar farm.

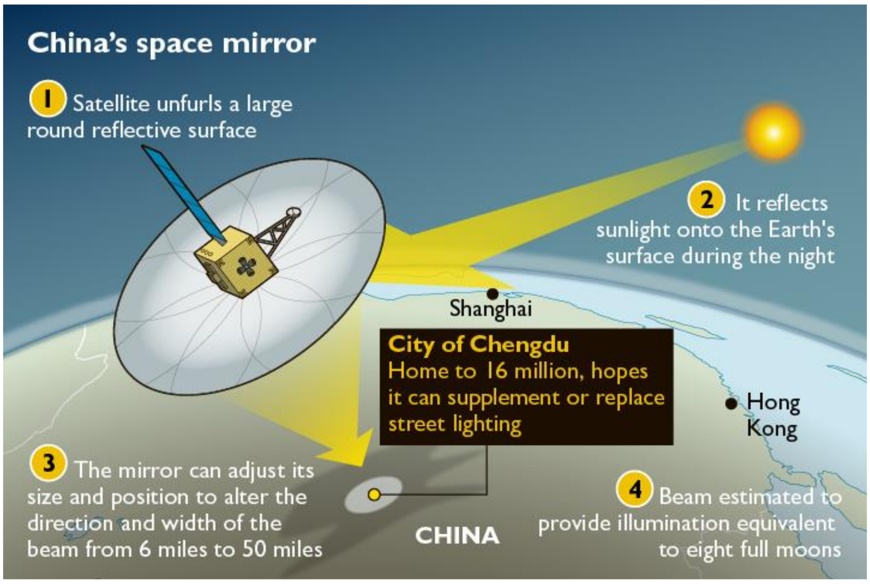


Figure 4: Chinese project to light up cities revealed in 2018

SPACE TRANSPORTATION OF DSR

- Functions of space transportation:
  - Payload transport and release;
  - Assembly;
  - Maintenance;
  - Cargo.
- Depending on the configurations, the following launchers can be used:
  - Heavy (> 20t LEO, Ariane-6-like);
  - Heavy+ (> 50 t LEO, Falcon-9 Heavy-like);
  - Super Heavy (>100 t LEO, Starship-like);
  - Super Heavy (> 150 t LEO).
  - These launchers could be partly or totally reusable.
- OTV could be used to transfer Reflector.
- Space Reflector could be used as a sail to transfer itself on another orbit.

Figure 5: Certain configuration of space reflectors could be placed in one piece by the future Ariane-6 launcher
Source: Dassault Aviation

Figure 6: In the past, huge launchers has been studied to launch parts of SBSPs. This illustration shows a Boeing/Nasa concept studied at the end of 70's
Source: Dassault Aviation

Figure 7: The literature on solar reflectors shows the need for some projects to use super-heavy launchers. For this reason, the consortium took into account the Protein initiative of ESA for its project
Source: Dassault Aviation

Assembly, maintenance and servicing of DSR

- Enabling technologies associate to maintenance and servicing:
  - Robotic Arms
  - In-Space Manufacturing
  - In-Space assembly
  - Refueling systems
  - Docking Mechanisms
  - De-orbiting kits
- Human intervention on DSR:
  - Human operation on orbit
  - Human transportation
  - Human live support on orbit

III. TECHNOLOGY MATURITY ASSESSMENT

Architecture module level 1	Building block	Example of enabling Technologies	Criticality : 0 (useless), 1 (nice to have), 2 (important), 3 (mandatory) – Mult. Small Reflec.	Mult. Large Reflectors	Single Large Flat Reflector	Single Large Parabolic Reflector	Reflect through laser pumping		Maturity evaluation (x = 8-9 during the decade) – To date (2023)	2025-2030	2030-2040	2040-2050
Launch	Launcher	Heavy (≥20t LEO)	1	0	0	0	1		9	X		
		Heavy+ (≥50t LEO)	2	1	1	1	3		9	X		
		Super Heavy (≥100t LEO)	3	3	3	3	2		9		X	
		Super Heavy+ (≥150t LEO)	2	2	2	2	1		6 saturn V		X	
		Partly reusable	2	2	1	1	1		9	X		
		Reusable	2	2	1	1	1		6		X	X
	Cargo return capacity	Cargo return capacity for recycling	2	2	2	2	2		9		X	X
Space infrastructure (1/2)	Structures, materials, and controls	Light weight unfoldable mirror materials	2	2	2	2	2		9	X		
		On orbit additive manufacturing for large parts	0	2	2	2	2		6		X	
		On orbit additive manufacturing multi materials	0	2	2	2	2		9		X	
		Innovative Critical Materials (e.g.: auto-repairing materials)	1	1	1	1	1		4		X	
		Light Metallic Alloys (to optimize weight/power ratio)	2	2	2	2	2		9	X		
		Multifunctional Materials/Metamaterials	1	1	1	1	1		4		X	
		Deployable structures and membranes	2	3	3	3	3		9	X		
		Inflatable structures	2	3	3	3	3		9	X		
	AOCS	Swarm coordinated flight management	3	3	0	0	0		9		X	
		Accurate pointing of multiple independent reflectors	3	3	0	0	0		9		X	
		Very high accuracy pointing and tracking to ground target	3	3	3	3	3		9		X	
		Real time attitude and shape control of large reflectors	0	3	3	3	3		9		X	
	Propulsion	Green propulsion	1	1	1	1	1		9		X	
		Chemical propulsion	2	2	2	2	2		9	X		
		Cold gas propulsion for fine control	2	2	2	2	2		9	X		
		LOX/LH2 Cryogenic propulsion	1	1	1	1	1		9	X		
		Electric propulsion	2	2	2	2	2		9	X		
		Water propulsion	1	1	1	1	1		8	X		
	On-orbit power management and distribution	Long duration efficient energy storage (Lithium-sulphur battery, enhanced fuel cells)	3	3	3	3	3		6	X		
		Reliable high-power distribution network, tackling issues of limited voltage in space	1	2	2	2	2		9	X		
		In-Space Power Generation	3	3	3	3	3		9	X		
Space infrastructure (2/2)	Space assembly, maintenance, and servicing	Robotic Arms, associated satellite standards and architectures	2	3	3	3	2		9		X	
		Human operation on orbit	0	0	1	1	0		9	X		
		Design for periodic orbital maintenance and dismantling	3	3	3	3	3		9	X		
		In-Space Manufacturing - Additive manufacturing - Advanced autonomous Robotic arms	2	3	3	3	3		6		X	
		In-Space Assembly and Integration - Advanced autonomous Robotic arms	1	3	3	3	3		8	X		
		Refueling systems / Refueling interface for life extension and its end effector	2	2	2	2	2		9	X		
		Docking Mechanisms	2	2	2	2	2		9	X		
		Human transportation to / in / from orbit	0	0	0	0	0		9	X		
		Human live support on orbit	0	0	0	0	0		9	X		
		De-orbiting Kits	1	1	1	1	1		9	X		
	Thermal control	Advanced thermal dissipation (MW)	0	1	1	1	3		9	X		X
		Deployable radiators	0	0	0	0	3		9			X
		Thermal fluidic loop systems	0	0	0	0	3		9			X
	Solar power generation	Deployable Structures	3	3	3	3	3		9	X		
		Acurate real time shape management of reflective panels	3	3	3	3	3		9		X	
		Structural and mirror surface oscillations damping	3	3	3	3	3		9		X	
		Formation flying and beam convergence (multiple mirrors)	0	3	2	2	0		9		X	
		Laser pumping	0	0	0	0	3		4		X	
		Orientation control for the Reflective panel	1	2	2	2	1		4		X	
	Collision management	Very accurate debris orbit prediction (few meters)	3	3	3	3	3		9		X	
		Comprehensive catalog of debris for which the energy is a concern	3	3	3	3	3		9		X	
		Dedicated shield spacecraft or shield robot on the structure	2	2	2	2	2		6		X	
		Avoidance strategy attitude/orbit/shape modification	2	2	2	2	2		9		X	
	Environment/population impacts	Permanent capability to stop the beam with mask deployment	2	2	2	2	3		1		X	
		Permanent capability to stop the beam with changin the mirror shape (divergent)	2	2	2	2	3		4		X	
		Light pollution minimization with shape, material (design) and attitude (control)	2	2	2	2	2		4		X	
		Design for end of life management dismantling or recycling	3	3	3	3	3		4		X	
		Permanent capability to orient the beam on clear zones	2	2	2	2	2		4		X	
		Permanent capability to stop the beam (e.g. make the beam divergent)	2	2	2	2	2		1		X	
	Wireless power transmission	*Out of scope in the DSR concept*										
								0				
Ground Infrastructure	Ground power reception	Photovoltaic panels						0	9	X		
		Concentrated panels (high efficiency)						0	9	X		
		Large spectrum panel (IR, visibles,…)						0	3		X	X
		Solar panel which convert sun in Hydrogen (directly)						0	6	X		
		CSP+ Molten salt						0	8	X		
		Floating support structures for offshore PV						0	5		X	
	Power to X	Enhanced fuel cells						0	7		X	
		Electrolyser						0	7		X	
		Inverters						0	9	X		
	Energy Transport	Liquid hydrogen container						0	7		X	
		Landbased transmission grid connection (Classic)						0	9	X		
		Landbased transmission grid connection (HVDC)						0	9	X		
		Offshore transmission grid connection (submarine HVDC)						0	8	X		
		Pipelines for Hydrogen						0	8	X		
		Pipeline for e-molecules (CH4, CH3OH, NH4,…)						0	9	X		
								0				
Platform systems	Communication between space and ground infrastructures	FDM/TDM and FDM/TDMA	3	3	3	3	3	1	9	X		

Figure 8: Technology Maturity Assessment
Sources listed in appendix

IV. DESIGN ASSUMPTIONS FOR KEY TECHNOLOGIES

REFLECTING MIRRORS

The table below describes the mail assumptions that will be used to design the architecture concept based on reflecting mirrors :

Type	Source	Applications	Mass/Surface	Material	Typical size
Classical mirror for space application	State of the art	Earth observation, astronomy for mirrors up to 2 m	30 kg/m²	Glass (Zerodur, SiC, …)	2 m
Large thin mirror	https://ntrs.nasa.gov/citations/19810016602	SBSP, solar sails	12 g/m² including platform	Thin (2µm) aluminized Kapton films (4 g/m²)	1000 m
Assembly of rigid plates	https://reader.elsevier.com/reader/sd/pii/S0008884622000631?token=37EB5B2830059332920B2486046BD06F805C5EE7E060C3047F2C6D387E47BE0246026DE498FE2C3C8168788C1BB65AFD&originRegion=eu	Solar arrays, SBSP	4 kg/m²	Silicium, Nida	thin plates of few meters large
Large deployable mirror	JWST	Astronomy, SBSP	28 kg/m²	Beryllium coated with gold	6.5 m
Rollable mirror	TAS	Solar sail, solar array, SBSP	2.5 kg/m²	Silicium	stripes of 2x50 m
Inflatable mirror	http://www.loft.optics.arizona.edu/documents/journal_articles/PID6309251.pdf	SBSP, solar sails	0.3 kg/m²	Mylar	25 m and more

Figure 9 – Main assumptions used to estimate the weight for a space reflecting mirrors

We will designed the mirrors needed based on a large thin mirror, offering the less waigted technology compared to others. Two additional factors should added:

- The AOCS components, that will be estimated with the need to flexibility required and the diameter of the mirror to be moved,
- The structure to assembly the mirrors

SOLAR PUMPED LASER

Without electricity, solar pumped laser is generated when a minimum sun energy is concentrated to stimulate the medium to emit photons

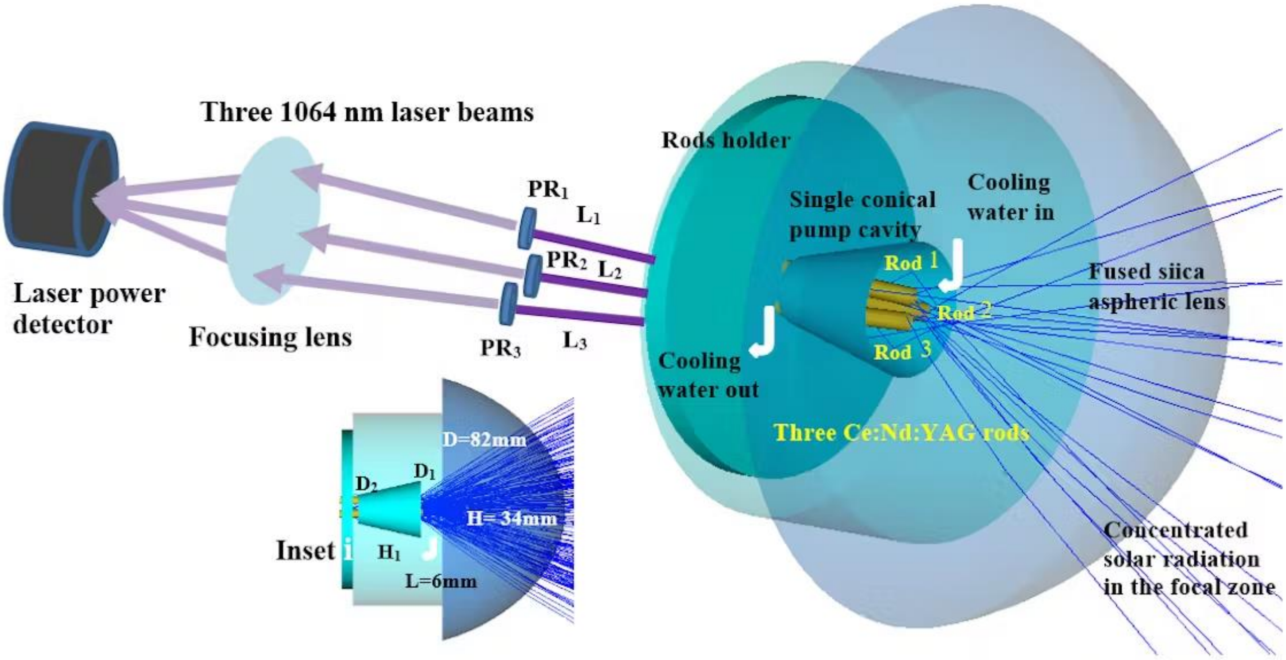


Figure 10: Solar pumped laser illustration
Source: : Dawei Liang, Universidade NOVA de Lisboa | NOVA · Department of Physics

Designing a solar pumped laser supposes to define value for the key components (value selected for SBSP design in strong blue)

Concentrator	Imaging concentration	Non imaging	**Imaging**							
	Surface	**Reflecting (mirror)**	Refracting (lense)							
	Shape	Flat	Hollow V	Parabolic cylindrical	Fresnel lens	Elliptical	Hyperboloidal	Conical	**Parabolic**	Pyramid
	Focus target	Line	**Point**							
Sunlight management control	Reactivity	No	Intermittency	**Continuous**						
	Maneuverability	One Axis	**Two Axis**							
Transmission energy mode		Direct	One piece	**Several optic fibers**						
Pumping type		**End of pipe**	Along the pipe							
Receiver	Form factor	Cylindrical	**Twist**							
	State of the medium	Gas	Liquid	**Solid**						
	Rare material	**Nd3+ (Neodyme)**	Erbium	Other						
	Host material	**YAG**	Glass	Other						

Preferred option as state of the art for the project (TBC)

Figure 11: Designing a solar pumped laser supposes to define value for the key components
Source: Arthur D. Little

Five KPIs define the performance of a solar pumped laser

KPI	Description	Key points	Range of value
Opening width (W)	Flat opening of the concentrator through which the solar radiation passes.	For a cylindrical or linear concentrator, it is characterized by the width, while for a surface of revolution, it is characterized by the diameter of the opening.	Depending of the power expected, few meters in general
Concentration rate (C)	Two definitions of concentration ratio : 1/Strictly geometric and is called "geometric or surface concentration ratio", 2/The second is in terms of the ratio of the measured intensity and is called "intensity concentration ratio" or "flux concentration ratio".	Surface Concentration Rate ($\boldsymbol{Carea}$) - ratio of the effective area of the opening to the area of the receiver. $Carea$ = Aa /Ar, where Aa is the area of the concentrator aperture and Ar is the area of the receiver (the receiver). Luminous Flux Concentration Rate ($\boldsymbol{Cflux}$) It is the ratio of the light intensity at the aperture to that of the absorber. $Cflux$ = Ia/ Ir, where Ia is the luminous flux value at the concentrator opening and Ir is the flux value luminous at the level of the opening of the receiver.	The values of the concentration rate vary from unity (which is the limiting case for a flat collector) to a few thousand for a parabolic concentrator
Acceptance angle (2$\boldsymbol{\theta a}$)	It is the angle with which the radiation of the light can deviate from the normal to the planar aperture and arrive at the receiver without a total or partial displacement of the collector.	Geometric optics and the second law of thermodynamics dictate that the maximum possible concentration for half an acceptance angle for a given manifold θa is: For hollow two-dimensional concentrators, $Cidéal$ $2D$ = 1 sin θa And for three-dimensional concentrators (cones, parabolas, pyramids): $Cidéal$ $3D$ = 1 sin^2 θa	Collectors with large acceptance angles require only occasional adjustments, while collectors with small acceptance angles need to be adjusted continuously.
Intercept factor (γ)	It is the fraction of the reflected radiation which is incident on the absorbing surface of the receiver		Values of γ greater than 0.9 are common values
Angle of incidence modifier (K)	These are concentrator contour errors, tracking errors, and errors displacement of the receptor from the focus	Errors can lead to enlargement or shift of the image thus affecting the transmittance of the system and the absorption of the receiver.	Concentration in practical systems is reduced by several factors

Table 1: Five KPIs define the performance of a solar pumped laser

The Nd:YAG is the most commonly used laser medium today and will be the preferred technology used for our design

Key benefits of this combinaison

- Neodymium-doped yttrium aluminum garnet (Nd:YAG) has a combination of exceptionally favorable properties for laser operation.
- Host YAG is tough, with good optical quality and high thermal conductivity.
- The cubic structure of the YAG promotes a narrow width of the fluorescence line, resulting in high gain and a low threshold for laser operation.
- For continuous or very high frequency repetition rate operation, the materials crystals provide higher gain and greater thermal conductivity

- It is possible to operate a neodymium-doped glass-based laser with a minor change in performance over a temperature range of $-100°C$ to $+100°C$.

Light in IR but other possible

- Under normal operating conditions, the laser at $Nd{:}YAG$ oscillates at temperature ambient at 1.0641 μm.
- It is however possible to obtain oscillations at other wavelengths by inserting standards or prisms dispersive in the resonator, specially using special resonant reflector like an output mirror, or by employing highly selective coated dielectric mirrors.
- These elements eliminate laser oscillation at the wavelength of 1.06 μm and provide conditions optimal at the desired wavelengths.
- With this technique, laser systems have been designed that use the transitions 946 nm and 1330 nm

Nd:YAG production state of art

Key points	Description	Typical value
Process manufacturing	Czochralski Method	Very slow growth rate, which is on the order of 0.5 mm/d. Of the typical balls 10 to 15 cm in length require a growth time of several weeks
Size of the receiver	The optical quality of these bars is normally quite good and comparable to the best quality ruby Czochralski or optical glass	Currently, rungs can be made with a maximum diameter of approximately 10 mm and lengths up to 150 mm. The assumption for design would be to get a 1m of diameter
The Neodymium concentration per atomic percent in the YAG	limited to 1.0 to 1.5%. Higher doping levels tend to reduce fluorescence lifetime, to broaden the linewidth and cause stress in the crystal, resulting in a poor optical quality	For continuous wave operation (CW: continuous wave), a low concentration doping (0.6 to 0.8%) is generally chosen to obtain good beam quality

Table 2: Nd:YAG production state of art

Some key points need to be further analyzed even if this technology offers significant benefits

- Temperature management :
  - The energy not collected by the receiver is diffused in non-coherent light and heat à a temperature regulation management is needed
- Durability of the receiver
  - How to avoid premature aging of the receiver?
- Design of the reflector and receiver to maximize efficiency and heat issue
- Maximum power possible in a specific wavelength with respect to environment on Earth

The table below summarizes the key assumptions selected to assess the design of this architecture

Key assumptions	Description	Value	Rationale
Reflector diameter	Size of the mirror to collect the sun energy	250 m (TBC)	Compatible with the size of collector to get the minimum energy to pump the laser The size 250m diameter is possible even larger
Technology for collector	The collector has a strong impact on performance	Nd:YAG	This technology is the best one as of today.
Size of the collector	The optical quality of these bars is normally quite good and comparable to the best quality ruby Czochralski or optical glass	1m of diameter	Currently, rungs are made with a maximum diameter of approximately 10 mm and lengths up to 150 mm. Extend the diameter seems to be possible according TAS expert
Power conversion efficiency	% of sun energy used by the collector to pump the laser	8%	Today, the current performance is 4,5% but experts forecast to jump to 8% in the decade and 20% in 2040's according laser experts (Pr. Dawei Liang – Bilbao University)
Laser wavelength	Wavelength generated by the collector. Closely linked with the technology used	1064 nm	Natural value for the technology selected In infrared and not visible, so no light pollution Wavelength not strongly absorbed by atmosphere (92%)

V. ASSESSEMENT OF NON MATURE KEY TECHNOLOGIES

Non-mature technologies were qualified to assess their performance on key factors that can influence design. First is the synthesis of and the space technologies, then the synthesis of and the ground technologies.

NON MATURE SPACE KEY TECHNOLOGIES

Maturity of key enabling space technologies

Building block		Example of enabling technologies	Maturity evaluation: To date (2023)	2020	2030	2040
Space Infra-structure	On-orbit power management and distribution	Long duration efficient energy storage (Lithium-sulphur battery, enhanced fuel cells)	6	6-7	7-8	
	Space assembly, maintenance, and servicing	In-Space Manufacturing - Additive manufacturing - Advanced autonomous Robotic arms	6	6-7	7-8	8-9
	Solar power generation	Solar Pumped Laser (SPL)	4	4	5-7	8-9
	Environment / population impacts	Permanent capability to stop the beam with mask deployment	1	1-4	5-7	8-9
		Permanent capability to stop the beam with changin the mirror shape (divergent)	4	4	5-7	8-9
		Design for end-of-life management dismantling or recycling	1	1-2	3-4	7-8

Figure 12 - Strong development efforts needed to bring SPL to maturity, and in-space manufacturing for multiple small mirrors

Technology : Long duration efficient energy storage (ex: Lithium-technology based battery)

Planning of maturation

TRL — 2020: 6-7 → 2030: 7-8

Main projects to increase maturity

Period	Project
20-30	• Long lifetime improvement • Increase safety with lower risk of incident between Li-ion reactions

Europe position for this technology :

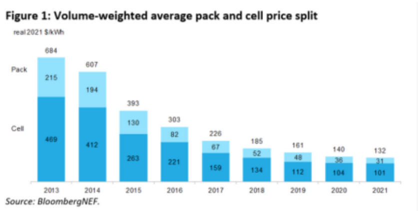
Weak | Tenable | Favorable | Strong | Clear | Leader

Potential impact on the SBSP competitiveness :

Low | Significant | Strong | Key

Performance KPI

KPI	Unit	Description	2020	2030	2040
Cost (cell/syst)	$/kWh	Cost per energy unit at 2 level: cell unit and system (cooling, BMS, …)	140	< 100	XXX
Energy Density	Wh/kg	The amount of energy that a battery can hold, measured by weight	XXX	80 -260	XXX
Life cycles	# of cycles	Number of cycles during which a battery can be discharged from 100% to 0% (100% DoD) or 50% (50% DoD), until its capacity falls to 80% of its initial capacity.	1000	3 500 - 10 000	XXX
Safety	-	Safety to control High Energy cost	Risk	OK	OK
Maintenance	-	Visual inspection required each	month	year	XXX
	CAPEX/year	Price of maintenance		1-5%	



Source: TAS, Arthur D. Little

31

Figure 13 - Technology : Long duration efficient energy storage (ex: Lithium-technology based battery)

Technology: in-space manufacturing - additive manufacturing - Advanced autonomous Robotic arms

Planning of maturation

TRL	2020	2030	2040
	6-7	7-8	8-9

Main projects to increase maturity

Period	Project
20-30	• Large structure printing in orbit
30-40	• Complex shape and material printing in orbit
40-50	• Full complex structure printing

Europe position for this technology :
Weak Tenable Favorable Strong Clear Leader

Potential impact on the SBSP competitiveness :
Low Significant Strong Key

Performance KPI

KPI	Unit	Description	2020	2030	2040
CAPEX	m€		100	50	10
Mass	kg	Mass of each robotic arm	100	60	30
Print rate	cm/day	Printing velocity	n.a.	10	100
Power consumption	W		300	200	150
Lifetime	Years		5	15	30
Print material	Resin/metal	Ability to deal with several material	resin	metal	both
Printing distance	m	Distance of material to be printed	10	100	1000

A maximum diameter of 1km has been selected for a unitary space mirror

Figure 14 - Technology: in-space manufacturing - additive manufacturing - advanced autonomous Robotic arms

Technology: solar pumped laser

Planning of maturation

TRL	2020	2030	2040
	4	5-7	8-9

Main projects to increase maturity

Period	Project
20-30	• Efficiency Improvement, flight demo
30-40	• Perf validation
40-50	• Upsizing

Europe position for this technology :
Weak Tenable Favorable Strong Clear Leader

Potential impact on the SBSP competitiveness :
Low Significant Strong Key

Performance KPI

KPI	Unit	Description	2020	2030	2040
Efficiency	%	Solar pumped laser efficiency	4.5	10	20
Lifetime	days	Max continuous duration performing solar pumping laser	0.1	10	1000
Power	W	Power produced per SPL unit	200	500k	50M
Mass	kg	Mass of the solar pumping device	TBD	TBD	TBD
Size	m	Size of the reflector	2	100	1000
Cost	M€	Cost of a single SPL unit	1	10	100

Huge potential for improvement

Figure 15 - Technology: solar pumped laser

Technology: permanent capability to stop the beam with mask deployment (for Direct Sun Reflecting)

Planning of maturation

TRL	2020	2030	2040
	1-4	5-7	8-9

Main projects to increase maturity

Period	Project
20-30	• Material definition ph0/A
30-40	• Small scale in orbit demo
40-50	• Large scale in orbit demo

Performance KPI

KPI	Unit	Description	2020	2030	2040
Efficiency	%shading	Ability to stop reflexion	10	30	90
Lifetime	years	No degradation with space environment	5	15	30
Deployment velocity	m²/s	Velocity to cover reflecting surface	10	8k	785k
Actuations nb	nb	Reliability of beam stopping mechanism	10	100	1000
Mass	kg	Overall mass of the apparatus	10	100	1000
Size	m	Typical size of the apparatus	0.1	1	10
Cost	k€	Overall cost of the apparatus	10	100	1000

Europe position for this technology :

Weak Tenable Favorable Strong Clear Leader

Potential impact on the SBSP competitiveness :

Low Significant Strong Key

Figure 16 - Technology: permanent capability to stop the beam with mask deployment (for Direct Sun Reflecting)

Technology: permanent capability to stop the beam with changing the mirror shape (divergent)

Planning of maturation

TRL	2020	2030	2040
	4	5-7	8-9

Main projects to increase maturity

Period	Project
20-30	• Actuator with mechanical analysis at space level
30-40	• Small scale in orbit demo
40-50	• Large scale in orbit demo

Performance KPI

KPI	Unit	Description	2020	2030	2040
Efficiency	%shading	Ability to stop reflexion	10	30	90
Lifetime	years	No degradation with space environment	5	15	30
Deployment velocity	m²/s	Velocity to cover reflecting surface	10	8k	785k
Actuations nb	nb	Reliability of beam stopping mechanism	10	100	1000
Mass	kg	Overall mass of the apparatus	10	100	1000
Size	M	Typical size of the apparatus	0.1	1	10
Cost	€	Overall cost of the apparatus	10	100	1000

Europe position for this technology :

Weak Tenable Favorable Strong Clear Leader

Potential impact on the SBSP competitiveness :

Low Significant Strong Key

Figure 17 - Technology: permanent capability to stop the beam with changing the mirror shape (divergent)

Technology: design for end-of-life management dismantling or recycling

Planning of maturation

TRL: 2020 1-2 — 2030 3-4 — 2040 7-8

Main projects to increase maturity

Period	Project
20-30	• Design for recycling and evaluation of interest wrt orbit choice
30-40	• Robotics demo in orbit
40-50	• In orbit recycling and manufacturing factory

Europe position for this technology :

Potential impact on the SBSP competitiveness :

Performance KPI

KPI	Unit	Description	2020	2030	2040
Recycling materials	% of use	Use of material candidates for recycling (design for recycling approach)	10	50	100
Dismantling capability	% building blocks	Satellite design for dismantling	10	50	100
Reusability	Overall % of reuse	Overall % of reuse for the platform	10	50	100
Robotics capacity	% of total mass	Robotics ability to deal with platform dismantling	10	50	100
Mass	Mass ratio	Return to Earth mass / recycled mass (if applicable)	10	50	100
Cost	% of cost	% wrt overall cost	20	10	5

Figure 18 - Technology: design for end-of-life management dismantling or recycling

NON MATURE GROUND KEY TECHNOLOGIES

Maturity of key enabling ground technologies

Building block		Example of enabling Technologies	Maturity evaluation: To date (2023)	2020	2030	2040
Ground Infra-structure	Ground power reception	Solar panel which convert sun in Hydrogen (directly)	4	3-4	7-8	
		PV Floating offshore	2	1-2	3-4	7-8
		Large spectrum panel (IR, visibles,…) for wavelength-adaptation	2	1-2	3-4	7-8

Figure 19 - Very immature wavelength-adapted solar panels, and strong efforts needed to bring solar fuel cells to maturity

Technology: Solar fuel cell (1/2)

Planning of maturation

TRL — **2023** 3-4 → **2030** 7-8

Main projects to increase maturity

Period	Project
23-30	• Finding a cheaper and safer solution for transforming and transporting hydrogen • Prototype development (reel)
30-40	• Industrial deployment of the technology in Europe and beyond. • Opportunity to Increase panel production with DSR concept

Europe position for this technology :

Weak — Tenable — Favorable — Strong — Clear — Leader

Potential impact on the SBSP competitiveness :

Low — Significant — Strong — Key

Demonstrator Solhyd HySun

Description

- **H2O:** water molecules in the air captured by the panel
- **Panel:** New recyclable materials, technologies with rooftop panels (Solhyd and HySun), new design
- **Weight panel:** 40kg per panel

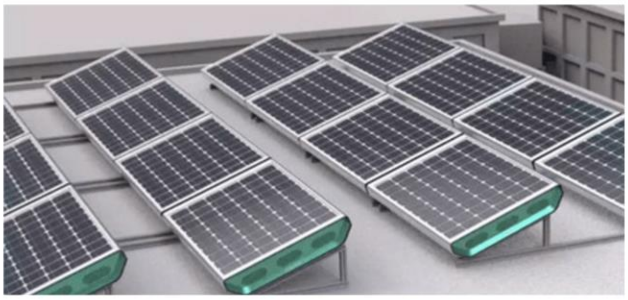


Figure 20 - Technology: Solar fuel cell (1/2)

Technology: Solar fuel cell (2/2)

Risk	Level (0 = low, 10 = high)	Description
Safety	8/10	Safety risks include damage to pipelines through leaks, particularly at joints
Sustainability	6/10	The environmental impact of hydrogen liquefaction?
Health	2/10	Potential impact of hydrogen logistics and transport on human health (in space and on earth, where applicable)

Performance KPI

KPI	Unit	Description	2020	2030	2040
H_2 COST	€/kg	The LCOE for the production and delivery of green H_2 in Europe must not exceed €5/kg.	XXX	5€/kg	1-3€/kg
Panel COST	€	Same price as PV silicium panel today	XXX	XXX	XXX
Performance	%	The efficiency of converting solar energy into hydrogen	10%	>= 40%	
Hydrogen production	kg/year	Annual production		6-12kg/y	
Hydrogène Power	MWh	hydrogen energy		4-8 MWh	
Life cycles	h	Not well known. A service life of around 4,000 to 5,000 hours per year before changing the electrolysis cells on normal Hydrogene plant.		TBD	TBD
Life Span	Years	The lifespan of hydrogen PV is determined by that of the solar panel and not the electrolysis part, because it can be changed (hydrogen production),		30 Years	
Maintenance	Total Cost	Operations and related costs for maintaining performance, ex: electrolyte change	18€ - 80€ per hours	< 18-80€ per hours	

Figure 21 - Technology: Solar fuel cell (2/2)

Please note that the quantity of production is estimated for a single solar fuel panel

Technology : PV floating offshore (1/2)

Planning of maturation

TRL	2020	2025	2030	>2030
	1-2	3-4	7-8	9

Main projects to increase maturity

Period	Project
20-30	• Deployment of 25 floating units and an electrical cable to power the port.
30-40	• Aiming in the near future, with partners, to produce 1GW in co-location with offshore wind energy • Large-scale deployment

Europe position for this technology :
Weak – Tenable – Favorable – Strong – Clear – Leader (marker at: Clear)

Potential impact on the SBSP competitiveness :
Low – Significant – Strong – Key (marker at: Strong)

Demonstrator Sun'Sète

Description

- **Distance:** <1,5 km from 2023 to 2030, in 2040 a target >1,5km
- **Size of float:** the dimensions of a float are 12x9x3,5m
- **Nbr panel:** on one float, we have twenty solar panels. the goal is to move up to 2 floats and then, by 2040, a target of 25 floats
- **Anchor:** the anchor is 3,5m long and weights 20 tons
- **Wavelength of the current PV:** 300-1100nm

Figure 22 - Technology : PV floating offshore (1/2)

Technology : PV floating offshore (2/2)

Risk	level	Description
Safety	4/10	There is a potential risk of accidents with swimmers or fishermen who may be present in the area.
Sustainability	7/10	The environmental impact remains fairly low, with a 60% obscuration rate and sufficient panel height. and tight inking to avoid scraping the seabed
Health	5/10	Conflicts over the distribution of maritime space

Performance KPI

KPI	Unit	Description	2023	2030	2040
Energy output	MW	Energy delivered by the floats over the total for the installation	5MW	10,20,100MW	1GW, 50GW
Power	kWc/hectare	The power that an installation can deliver per hectare	600kWc /1h	556kWc/ha	
Performance	%	Identical to current silicon panels	13% - 18%	16%-24%	>24%
Life span	Years	Estimating the lifespan of solar panels at sea, Development of new structures using materials resistant to corrosion in the marine climate.	10 years	XXX	20/25 years
Maintenance	Total cost	Maintenance will be very complex, given that the installation is 1.5 km from the coast, with salt, marine waste. And use of the PV cleaning robot	10/12€ per panel	7/8€ per panel	<7€ per panel
Environment	m	Acceptable wave level	10m	12m	15m

Figure 23 - Technology : PV floating offshore (2/2)

Technology : Panel capable of better absorbing wavelengths of 1064 nm (1/2)

Planning of maturation

TRL — 2020: 1-2 — ? — 2025: 3-4 — ? — 2035 / 2040: 7-8

Main projects to increase maturity

Period	Project

Europe position for this technology :

Weak — Tenable — Favorable — Strong — Clear — Leader

Potential impact on the SBSP competitiveness :

Low — Significant — Strong — Key

Description

The current Silicon PV panel absorb wavelengths of 1064nm with an efficiency which is similar (quite lower) than the sun light with several wavelengths

To increase the efficiency, two solutions are possible :

- Reduce the wavelengths to about 800-900nm
- Check or create new PV with different semiconductor in the cells which absorb the wavelength of 1064nm
  - InGaAs cells have a better spectral response in the infrared spectrum. Commercially available but has a considerably higher cost
  - Other materials could be considered but currently not commercially available

It will be interesting to test / develop specific panel if the Solar Pump laser emerges

Target an efficiency of about 50%-60%.

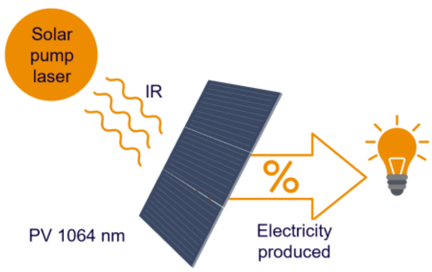


Figure 24 - Technology : Panel capable of better absorbing wavelengths of 1064 nm (1/2)

Technology : Panel capable of better absorbing wavelengths of 1064 nm (2/2)

Risk	level	Description
Safety	4/10	Safety risks include damage to pipelines through leaks, particularly at joints
Sustainability	6/10	The environmental impact of rare materials included in panel
Health	2/10	Potential impact of rare materials on health of workers

Performance KPI

KPI	Unit	Description	2023	2030	2040
Energy output	MW	Identical to current silicon panels	5MW	10,20,100MW	1GW, 50GW
Power	kWc/hectare	Identical to current silicon panels	600kWc /1h	556kWc/ha	
Performance	%	Panels in development: expected performance		60%	
Life span	Years	Panels in development: expected performance		20/25 years	
Maintenance	Total cost	Panels in development: expected costs are same as traditional solar PV		5 €/kW solar/y	

Figure 25 - Technology : Panel capable of better absorbing wavelengths of 1064 nm (2/2)

ARTHUR D LITTLE

APPENDIX

TECHNOLOGY MATURITY ASSESSMENT: SOURCES

Architecture module level 1	Building block	Example of enabling Technologies	Sources
Launch	**Launcher**	Heavy (≥20t LEO) Heavy+ (≥50t LEO) Super Heavy (≥100t LEO) Super Heavy+ (≥150t LEO) Partly reusable Reusable	https://en.wikipedia.org/wiki/Comparison_of_orbital_launch_systems https://ariane5.cnes.fr/fr/caracteristiques-techniques https://www.spacex.com/vehicles/falcon-heavy/ https://www.nasaspaceflight.com/2022/11/artemis-i-launch-nov/ https://www.spacex.com/vehicles/starship/ https://www.nasaspaceflight.com/2017/08/spacex-falcon-9-launch-crs-12-dragon-mission-iss/ https://www.spacex.com/media/starship_users_guide_v1.pdf https://www.grc.nasa.gov/WWW/BGH/hihyper.html
Launch	**Cargo return capacity**	Cargo return capacity for recycling	
Space infrastructure (1/2)	**Structures, materials, and controls**	Light weight unfoldable mirror materials On orbit additive manufacturing for large parts On orbit additive manufacturing multi materials Innovative Critical Materials (e.g.: auto-repairing materials) Light Metallic Alloys (to optimize weight/power ratio) Multifunctional Materials/Metamaterials Deployable structures and membranes Inflatable structures	https://www.nasa.gov/content/goddard/the-amazing-anatomy-of-james-webb-space-telescope-mirrors/AA15 https://jwst.nasa.gov/content/observatory/ote/mirrors/index.html https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Shaping_the_Future/In-Orbit_Manufacturing_of_Very_Long_Booms https://www.space.com/darpa-us-military-space-manufacturing https://www.nasa.gov/oem/inspacemanufacturing https://www.nasa.gov/nextstep/fablab https://link.springer.com/article/10.1007/s12567-021-00365-5 https://www.researchgate.net/publication/359818865_Aluminium_Alloys_in_Space_Applications_A_Short_Report https://iopscience.iop.org/article/10.1088/2399-7532/ab5242/pdf https://www.esa.int/Science_Exploration/Space_Science/Webb/Webb_deployment_complete https://airandspace.si.edu/collection-objects/communications-satellite-echo-1/nasm_A20030090000 https://www.youtube.com/watch?v=t3nRfGUwHs4 https://www.eoportal.org/satellite-missions/iae#spartan-207
Space infrastructure (1/2)	**AOCS**	Swarm coordinated flight management Accurate pointing of multiple independent reflectors Very high accuracy pointing and tracking to ground target Real time attitude and shape control of large reflectors	https://www.esa.int/Enabling_Support/Operations/Swarm_operations https://en.wikipedia.org/wiki/Satellite_constellation#List_of_satellite_constellations https://en.wikipedia.org/wiki/Global_Positioning_System https://www.sciencedirect.com/science/article/pii/S1474667015332122 https://reader.elsevier.com/reader/sd/pii/S1000936120305847?token=94541F4DDCA2DE0DF564A054739F284BDC4D76311BFB7D9B82477B9C33DC5730249F6FC187AC32A09D4272BC47C48B19&originRegion=eu-west-1&originCreation=20230515135525 https://ntrs.nasa.gov/api/citations/20100009694/downloads/20100009694.pdf?attachment=true https://pdf.sciencedirectassets.com/271642/1-s2.0-S0273117722X00264/1-s2.0-S027311772200936X/main.pdf?X-Amz-Security-Token=IQoJb3JpZ2luX2VjEO3%2F%2F%2F%2F%2F%2F%2F%2F%2F%2FwEaCXVzLWVhc3QtMSJHMEUCIA7UEYRip32kZpW3vSA0kVZURnEGG
Space infrastructure (1/2)	**Propulsion**	Green propulsion Chemical propulsion Cold gas propulsion for fine control LOX/LH2 Cryogenic propulsion Electric propulsion Water propulsion	https://www.nasa.gov/mission_pages/tdm/green/gpim-nears-completion.html https://www.nasa.gov/sites/default/files/atoms/files/4._soa_in-space_propulsion_chapter_2022_0.pdf https://www.mdpi.com/2226-4310/8/1/20 https://www1.grc.nasa.gov/research-and-engineering/chemical-propulsion-systems/ https://www.nasa.gov/sites/default/files/atoms/files/4._soa_in-space_propulsion_chapter_2022_0.pdf https://www.nasa.gov/exploration/systems/sls/fs/rl10engine.html https://www.esa.int/Enabling_Support/Operations/SMART-1
Space infrastructure (1/2)	**On-orbit power management and distribution**	Long duration efficient energy storage (Lithium-sulphur battery, enhanced fuel cells) Reliable high-power distribution network, tackling issues of limited voltage in space In-Space Power Generation	https://www.nasa.gov/sites/default/files/atoms/files/ptd_factsheet_23apr2018_508.pdf https://www.nasa.gov/smallsat-institute/sst-soa/in-space-propulsion https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Shaping_the_Future/High_Specific_Energy_Lithium_Sulfur_cell_for_Space_applications https://www.airbus.com/en/newsroom/news/2017-06-all-electric-propulsion-satellites
Space infrastructure (2/2)	**Space assembly, maintenance, and servicing**	Robotic Arms, associated satellite standards and architectures Human operation on orbit Design for periodic orbital maintenance and dismantling In-Space Manufacturing - Additive manufacturing - Advanced autonomous Robotic arms In-Space Assembly and Integration - Advanced autonomous Robotic arms Refueling systems / Refueling interface for life extension and its end effector Docking Mechanisms Human transportation to / in / from orbit Human live support on orbit De-orbiting Kits	https://www.nasa.gov/smallsat-institute/sst-soa/power#_Toc118790655 https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/International_Space_Station/European_Robotic_Arm https://en.wikipedia.org/wiki/Canadarm https://www.nasa.gov/mission_pages/station/main/index.html https://www.nasa.gov/mission_pages/hubble/servicing/index.html https://reader.elsevier.com/reader/sd/pii/S0008884622000631?token=37EB5B2830059332920B2486046BD06F805C5EE7E060C3047F2C6D387E47BE0246026DE498FE2C3C8168788C1BB65AFD&originRegion=eu-west-1&originCreation=20230515144446 https://spectrum.ieee.org/gitai-space-robot https://en.wikipedia.org/wiki/Orbital_Express https://nexis.gsfc.nasa.gov/robotic_refueling_mission.html https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/ATV/Europe_s_automated_ship_docks_to_the_ISS https://en.wikipedia.org/wiki/NASA_Docking_System https://en.wikipedia.org/wiki/Human_spaceflight#Milestones https://www.nasa.gov/content/life-support-systems
Space infrastructure (2/2)	**Thermal control**	Advanced thermal dissipation (MW) Deployable radiators Thermal fluidic loop systems	https://www.nasa.gov/smallsat-institute/sst-soa/deorbit-systems#_Toc96425749 https://www.researchgate.net/publication/237119042_Heat_Transfer_Analysis_of_a_Closed_Brayton_Cycle_Space_Radiator https://jwst.nasa.gov/content/observatory/sunshield.html https://www.nasa.gov/pdf/473486main_iss_atcs_overview.pdf
Space infrastructure (2/2)	**Solar power generation**	Deployable Structures Acurate real time shape management of reflective panels Structural and mirror surface oscillations damping Formation flying and beam convergence (multiple mirrors) Laser pumping Orientation control for the Reflective panel	https://www.nasa.gov/smallsat-institute/sst-soa/thermal-control#_Toc120613728 https://www.esa.int/Science_Exploration/Space_Science/Webb/Webb_deployment_complete https://jwst.nasa.gov/content/observatory/sunshield.html https://ntrs.nasa.gov/api/citations/20100009694/downloads/20100009694.pdf?attachment=true https://pdf.sciencedirectassets.com/271642/1-s2.0-S0273117722X00264/1-s2.0-S027311772200936X/main.pdf?X-Amz-Security- https://svs.gsfc.nasa.gov/12546 https://www.researchgate.net/publication/258719158_Vibration_Damping_for_the_Segmented_Mirror_Telescope https://ietresearch.onlinelibrary.wiley.com/doi/epdf/10.1049/iet-map.2015.0811 https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7861906 https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8669301 https://www.nature.com/articles/s42005-020-0326-2
Space infrastructure (2/2)	**Collision management**	Very accurate debris orbit prediction (few meters) Comprehensive catalog of debris for which the energy is a concern Dedicated shield spacecraft or shield robot on the structure Avoidance strategy attitude/orbit/shape modification	https://www.nasa.gov/mission_pages/station/research/news/sensor_to_monitor_orbital_debris_outside_iss https://www.nasa.gov/offices/nesc/articles/space-debris https://en.wikipedia.org/wiki/United_States_Space_Surveillance_Network https://hvit.jsc.nasa.gov/shield-development/
Space infrastructure (2/2)	**Environment/population impacts**	Permanent capability to stop the beam with mask deployment Permanent capability to stop the beam with changin the mirror shape (divergent) Light pollution minimization with shape, material (design) and attitude (control) Design for end of life management dismantling or recycling Permanent capability to orient the beam on clear zones Permanent capability to stop the beam (e.g. make the beam divergent)	https://www.sciencedirect.com/science/article/abs/pii/S0273117705009397 https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6902594 https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9093992 https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6023510 https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9597056 https://blogs.esa.int/cleanspace/2019/09/09/esa-is-looking-into-futuristic-in-orbit-services-recycling-satellites/
Space infrastructure (2/2)	**Wireless power transmission**	*Out of scope in the DSR concept*	
Ground Infrastructure	**Ground power reception**	Photovoltaic panels Concentrated panels (high efficiency) Large spectrum panel (IR, visibles,…) Solar panel which convert sun in Hydrogen (directly) CSP+ Molten salt Floating support structures for offshore PV	Laborelec expert Laborelec expert Laborelec expert hysun, engie Laborelec expert Laborelec expert
Ground Infrastructure	**Power to X**	Enhanced fuel cells Electrolyser Inverters	https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide Laborelec expert Laborelec expert
Ground Infrastructure	**Energy Transport**	Liquid hydrogen container Landbased transmission grid connection (Classic) Landbased transmission grid connection (HVDC) Offshore transmission grid connection (submarine HVDC) Pipelines for Hydrogen Pipeline for e-molecules (CH4, CH3OH, NH4,…)	https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide Laborelec expert Laborelec expert Laborelec expert Laborelec expert Laborelec expert
Platform systems	**Communication between space and ground infrastructures**	FDM/TDM and FDM/TDMA	