ARTHUR D LITTLE

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

TN3 – ARCHITECTURE SELECTION REPORT

REPORT TO
EUROPEAN SPACE AGENCY (ESA)

July 17th 2023 – Revision 2

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

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1. VERSIONING

Version	Date	Comment
ESA TALDA - TN3 - Architecture Selection Report.Revision1	24/05	
ESA TALDA - TN3 - Architecture Selection Report.Revision1.1_PostSKR	20/06	Post SKR meeting: comments and correction added to Word
ESA TALDA - TN3 - Architecture Selection Report.Revision1.2	28/06	Added versioning tab Implemented changes from Excel in Word
ESA TALDA - TN3 - Architecture Selection Report.Revision2.1	17/07	Addition the architecture pruning content to select the reference architecture
ESA TALDA - TN3 - Architecture Selection Report.Revision2.2	22/08	Post ASR RIDs comments added
ESA TALDA - TN3 - Architecture Selection Report.Revision2.3	28/08	Appendix updated with all scenarios

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CONTEXT & OBJECTIVES

3.1 INTRODUCTION

The challenge for the next weeks leading to the ASR review at the end of July is to define the reference architecture that will be specified in the second part of the year. For this, the three WPs contribute to it and are generally to be carried out in parallel
• WP 100: Stakeholders' needs and requirements
• WP 200: Review of the state of the art and identification of key technologies for the concept
• WP 300: Trade space exploration, i.e. list of possible architecture configurations (in relation to requirements and using key technologies)

Before precisely defining the system in detail, it is still necessary to choose the best configuration given the criteria. We have seen in the WP100 that there are several use cases to consider, and we must therefore choose the best couple “Use case – Architecture configuration”. For this, it is necessary to define the key dimensions of each segment and the possible values, then the links between dimensions.

The objective of the document is to:

- Explore the trade-space of candidate architectures,
- Support the identification of preferred architecture(s)
- Define a narrower subset of the trade-space compliant with the pre-selected use cases

3.2 MAIN CONCEPT

Keeping the elements of decision making in mind, the trade space analysis process is based on the following steps:

- define criteria,
- define alternatives,
- evaluate alternatives, and
- select/commit to a best-fit alternative for implementation.

“The trade space exploration methods, processes, and tools should enable deeper consideration of system design alternatives while keeping the space as open as possible to address resiliency and robustness to changing conditions and constraints.” (Spero, Avera, Valdez, & Goerger, 2014).

Trade: an **attribute or characteristic** of the target architecture with associated benefits and opportunity costs which may be exchanged in part or totality.

Trade space: the **bounded** area which considers the range of possible values (inherent or applied) for any number of attributes and characteristics, the relationships between them, and impacts on potential (design, decision, operational) outcomes.

Trade space analysis: the search of the bounded space to **highlight the relationships between trades, their values, and outcome objectives**.

4. LIST OF TRADES & ARCHITECTURE MATRIX

Considering the global architecture design, it is important to consider three types of trades:
- The system requirements, especially the ones that are not mandatory but valuable,
- The trades associated to the ground segment,
- The trades associated to the space segment.

4.1 REQUIREMENTS AND NEEDS

Although all the requirements will impact the architecture to some extent, we highlight three of them that will have the most impact for the design of our DSR concept:
- The total energy produced by the SBSP system should be 750TWh in 2050 : Based on the energy range produced by each ground plant, it will lead to estimated number of plants needed
- The spot size should be minimized for light pollution when ground segment is located in inhabited area
- The minimum power density to activate the cells should higher than 200W/m^2

Other requirements have to be considered but these ones are the most mandatory for the full SBSP system.

4.2 TRADES FOR GROUND SEGMENT

Considering the global architecture, it is possible to highlight and define a first list of key dimensions for the ground segment:

Trade	Description	Potential values	Remarks
Final Output	As described in the TN1 document, major use cases are based on the outputs generated by the system. Two most promising outputs have been pre-selected. This output could vary upon the location of the plant	Electricity direct to the grid	ESA preferred output, even if electricity represents ~20% of the energy consumed by Europe
		Solar molecules	Mostly H2, but potentially others derivatives like Ammonia, Methane…
Location of the GPS plant	The location should take into account the spot size generated by the SPS, due to light pollution and environmental impact. The location impacts also the load factor (less clouds near the equator) and the variation of the day duration (quite stable near equator, variation in Europe)	Onshore Europe	ESA preferred option but it is more and more difficult to find new location. The spot size is the biggest drawbacks for a full deployment in this option
		Offshore Europe	Can be interesting as there could be some available locations to deploy DSR farms with a quite large spot size (especially combined with offshore wind).
		Outside Europe	As this level, we do not split into several areas but only consider areas where any spot size can be accepted Some areas offer very favourable load factor (dry weather)
Power range / GPS	Due to technical constraints, the minimum power of the plant has to respect some limits, mainly by output	Less than 1GW	Easier connection to the grid to avoid too much regulation perturbance
		From 1 to 5GW	Could be used for electricity combined with large storage capacity in order to inject in the grid only the needed energy
		More than 5GW	Seems to be the minimum for producing solar molecules and H_2 with the critical size (please note that the Graveline nuclear plant power is about 5GW)
Illumination period	The period of the day where the SPS send energy is key for the sizing case	Only dawn and dusk	Typically 2h in the morning and before night
		Extended day	From 7am to 9pm (increase the energy received during the whole working day time)
		24/7	Most interesting to maximize the ROCE of the infrastructure but not possible near population. Could have an environmental impact
		Photovoltaic panel	Classic technology to generate electricity

Type of panels	The technology to convert the sun energy onto the final output	Photovoltaic panel combined with electrolysis	Current technology to generate H2 from sun – Low yield rate
		Solar fuel panel	New emerging technology to generate H2 with a direct reaction
		Adapted wavelength panel	Emerging technology to design panels that maximize the yield for the laser wavelength (1064nm)

Table 1 – Trade space for ground segment

4.3 TRADES FOR SPACE SEGMENT

The table below identifies a first list of what could be the trades to consider for selecting the best architecture and the range of values for each.

Trade	Description	Potential values	Remarks
Orbit distance	The orbit will determine the spot size and the move between the GPS and the SPS if it is not GEO	GEO	Simplest orbit as the SPS is fixed for the GPS on earth. Single satellite system may suffices.
		SSO 6-18LST (1400km)	Lowest orbit without eclipse but orbital plane near the dawn and dusk. Constellation is required.
		890km	Ideally to minimize the spot size. Constellation is required.
		Other	Other elliptical orbit non considered as more interesting than SSO wrt illumination
Orbit inclination	The inclination determine the earth area covered by the SPS	~0° (Equatorial and south of Europe)	Allow to target ground segment near equator by keeping illumination at the zenith
		I°	Optimal orbit to cover the targeted areas of the plants (inclination imposed by SSO orbit definition)
		90°	To target polar and north of Europe where offshore winds offer available areas to accept large solar farms
Payload technology	The form factor the SPS will be key to determine the overall performance of the system	Multi Small	Typically, a group of small satellites with mirror up to 100 m of diameter, pointed to target a single point at earth
		Multi Large	Typically, a group of satellites with mirror of 1000 m of diameter, pointed to target a single point at earth
		Single Large Flat	A single satellite targeting one GPS with a flat mirror of several km^2 (state of the art of the DSR technology) to generate enough energy to activate cells
		Single Large Shaped (parabolic)	In this case, the mirror is shaped to focuse the light and reduce the spot size on earth
		Solar pumped Laser	System allowing to generate a laser beam from solar flux, without electric conversion, after concentrating the Sun light received. The light beam has a very narrow size providing a high power density spot size.

Table 2 - Trade space for space segment

Concerning sizing case for mirrors in LEO: excessive energy could be stored in a buffer (hydrogen, Li Batteries…) to be managed by the ground segment.
However it could be a potential advantage to be able to produce more than 1GW especially for off-grid hydrogen ground stations.

4.4 ARCHITECTURE MATRIX

Based on these factors, it possible to determine the potential links between each, like described in the table below. Each case of this table identified is a factor impacted by the other. For instance, the first one “Output” is impacted by the second “Location”

	Output	Location	Panel technology	Power / GPS	Orbit distance	Orbit inclination	Payload technology
Output							
Location	Yes						
Panel technology	Yes	No					
Power / GPS	Yes	No	No				
Orbit distance	No	No	No	Yes			
Orbit inclination	Yes	Yes	No	No	No		
Payload technology	No	Yes	Yes	Yes	Yes	Yes	

Table –3 - Architecture Trade Space at the trade level

It is clear that the payload technology is the key driver to determine the potential short-list of architectures, due to the following reasons:

- It defines the spot size with the orbit distance
- The spot size determines the environmental impact (light pollution) and so the selection of the potential locations
- The spot size determines also the power received by the ground plant, especially if the ground segment do not cover the full spot size

The next table presents the detailed matrix for each estimated value of each trade (0 = impossible fit, 5 = excellent fit), facilitating the final configuration after the pre-selection of the main options related to ESA set of requirements.

0 Impossible
5 Perfect fit

			Output		Location			Panel technology				Power/ GPS			Orbit Altitude			Orbit Inclination			Payload technology				
			Electricity	Green Molecule	OnShore Europe	Off Shore Europe	Outside	Normal PV panel	PV combined with electrolysis	Solar fuel cell	Wavelength adpated PV panel	<1GW	1-5 GW	>5GW	GEO	SSO	600km	0°	i°	90°	Multi Small	Multi Large	Single Large Flat	Single Large Shaped (parabolic)	Solar pumped Laser
Ground	Output	Electricity																							
		Green Molecule																							
	Location	OnShore Europe	5	3																					
		Off Shore Europe	4	3																					
		Outside	0	3																					
	Panel technology	Normal PV panel	5	0																					
		PV combined with electrolysis	0	5																					
		Solar fuel cell	0	5																					
		Wavelength adpated PV panel	5	0																					
	Power / GPS	<1GW	5	1																					
		1-5 GW	3	2																					
		>5GW	1	4																					
Space	Orbit distance	GEO			2	3	5					2	1	0											
		SSO			5	5	5					3	3	3											
		600km			5	5	5					3	3	3											
	Orbit inclination	0°	0	4	0	0	5																		
		i°	4	4	5	5	4																		
		90°	4	4	4	4	5																		
	Payload technolo	Multi Small			5	5	5	3	3	3	3	3	3	3	1	2	3								
		Multi Large			2	2	2	3	3	3	3	3	3	3	1	1	1								
		Single Large Flat			2	2	2	3	3	3	3	3	3	3	0	0	0								
		Single Large Shaped (parabolic)			1	1	1	4	4	4	4	3	3	3	0	0	0								
		Solar pumped Laser			3	5	5	3	2	3	5	5	5	5	4	3	3								

Table 4– Architecture Trade Space at the value level

5. FOCUS ON THE PAYLOAD TECHNOLOGY

5.1 COMPARISON OF PAYLOAD TECHNOLOGY MIRROR FOR A SINGLE ORBIT

Considering the strengths and weaknesses of each technology, the table below outlines the best ones considering key criteria to select the good one for the reference architecture:

0 Not performant
5 Very good performance

Payload technology	Assumption of the reflector dimension	Techno accessibility	Power provided in a 15km2 area	Spot size in GEO	Spot size in SSO	Light pollution	Altitude control	Scalability	Complexity of deployment in space	Launching complexity	Targeting ground segment	Evaluation note
Criteria weight		**2**	**3**	**1**	**2**	**2**	**2**	**3**	**2**	**1**	**2**	**20**
Multi Small Mirrors	Diameter 100m	5	2	0	1	1	4	4	4	4	3	58
Multi Large Mirrors	Diameter 1km	2	1	0	1	1	3	3	2	2	3	38
Single Large Flat Mirror	Diameter >>1km	2	1	0	1	1	1	1	1	1	1	21
Single Large Shaped Mirror (parabolic)	Diameter >>1km	1	2	0	2	1	1	1	1	1	1	24

Table –5 - Payload technology qualitative evaluation

Except for the solar pumped laser which is described in the next section, the **multi small mirrors** offers the best solution compared to multi large:

- It is **easier to control the** attitude of the cluster and each satellite. As the satellites have a lower inertia, their control is easier than with large mirrors
- It is **more scalable with a progressive deployment** without any massive in space manufacturing : deployment technologies for 100m diameter mirrors exists and the robotic assembly technologies are also available. On the other hand, large mirrors, say 1000m diameter, implies complex technologies and require in orbit assembly leading to a much complex final orbital structure
- It could be **launched by today heavy launchers**,
- It is **easier to manage the pointing** towards the GPS with small mirrors than large ones
- Each mirror can be used to shape a “virtual global mirror” that target the GPS with an **optimized spot size**

The evaluation of the single flat mirror increases the weaknesses of the multi large mirrors without clear advantage:

- The attitude and pointing control are more difficult than multi large, due to the inertia inertia and the flimsiness of the structure
- The shaped large mirror can have a better spot size in lower orbits, but with a very low impact

Based on these qualitative analysis, we can conclude that the multi small mirror technology seems to be the most promising choice.

5.2 PRELIMINARY SIZING CASES FOR PAYLOAD TECHNOLOGIES BASED ON DIRECT SUN REFLECTING MIRROR

We have designed to a first order some-approach sizing scenarios to determine the size of the mirrors to reach the minimum of energy for PV plants.

These scenarios have been designed to get a range of magnitude and especially do not consider some factors:

- The attenuation due to the atmosphere (roughly 30% of losses) is not included.,
- The impact of the angle when the SPS is not at the zenith of the GPS.,
- The existence of an angle between [mirror-sun] direction and [mirror-target on ground] direction.,
- The impact of the of Earth oblateness.

The table below shows the simple model designed:

Parameter	Value	Unit	Source / remark
Sun Flux	1300	W/m2	Internet
Sun diameter	1.39E+09	m	Internet
Sun Distance	1.50E+11	m	Internet
Sun aspect angle	0.0093	rad	Landis article
orbit altitude	600	km	Input
mirror diameter	1000	m	Input
number of mirrors	1		Input
diameter of spot on earth (max)	5.57	Km	Sun aspect angle x Orbit altitude - Rough estimation
Total reflected Energy on Earth	1021	MW	Mirror surface x Sun flux x Nb mirror
Irradiance on Earth	42	W/m2	Energy / spot size on earth
Earth radius	6378.00	Km	internet
Mu	3.99E+14	m3/s^2	Geocentric gravitational constant
orbit radius	6978.00	km	Orbit altitude + earth radius
orbit speed	7557.94	m/s	Average speed on orbit
orbit angular rate	0.0011	rad/s	Average angular speed
minimum elevation	30.00	deg	Minimum of elevation to illuminate the ground
Visibility window (orbit at equator)	4.42	min	Duration for each revolution where the GPS is visible

Table 6 – Model built to estimate the key parameter of an architecture

The main inputs are the altitude and the mirror size. In addition to physical laws and parameters, the model allows to estimate :

- The spot size
- The irradiance on earth (W/m2)
- The visibility window in minutes

The weight to launch will also be calculated for each scenario, as it can be considered as a good proxy of the deployment cost.

Based on this simplified model, we ran several scenarios computed to better assess the value of payload technology for mirrors according to the orbit. In these scenarios, we only consider flat mirrors, the potentiality of curved mirrors are analysed independently for each scenario.

Scenario		Mullti Small in GEO	Multi Large in SSO	Single Flat in SSO	Multi Small in SSO	Mullti Large in LEO	Single Large in LEO	Multi Small in LEO	Multi Small in LEO
Parameter	Unit	A	B	C	D	E	F	G	H
Orbit altitude	km	36000	890	1600	1600	600	600	600	800
Mirror diameter	m	1000	1000	5100	100	1000	2200	100	100
Mirror surface	ha	79	79	2043	1	79	380	1	1
Results	Unit								
Irradiance on Earth	W/m2	0.012	19.04	153.22	0.06	41.891	202.752	0.419	0.236
Visibility window	Min	PERMANENT	6.3	11	11	4	4	4	6
Diameter of spot on earth (max)	Km	334	8.3	15	15	6	6	6	7
Nb SPS to reach 1000W/M2	#	85938	53	7	16976	24	5	2388	4244
Weight to launch / cluster	t	1349911	833	2860	2667	377	380	375	667
Nb of clusters to illuminate 2h	#	1	20	11	11	29	29	29	22
Associated weight to launch	t	1349911	16650	31459	29332	10933	11024	10878	14666
Power received in 15km2 before attenuation	GW	15	15	16	15	15	15	15	15
Attenuation due to atmospheric diffusion	%	70%	70%	70%	70%	70%	70%	70%	70%

Table 7 – Results of the height scenarios considered on mirror payload technology and orbit

The table presented as a preliminary analysis before designing the DSR architecture estimate the number of SPS to get 1000W/m2 on the ground whatever the spot size is. For a ground station of a given surface (here 15km2), it will produce the same power by design.

Please note that propellant budget is sized without solar pressure but with very conservative parameters. No significant impact with preliminary calculations with solar pressure.

Scenario A

This scenario is based on a GEO SPS, typically with a 1km diameter mirror (flat). It clearly shows the limit of this configuration:

- The spot size is more than 300km of diameter, roughly the size if Ireland.
- The irradiance on earth is extremely low, because all the energy collected in diffused in the total spot area, leading to deploy more than 86 000 single SPS to get 1000W/m^2, with a huge tons to launch (270kt[1]), delivering 88 TW on ground, or 760 000 TWh per year (more than actual humanity need). Clearly not the scenario requested by ESA.

However, the power received in the ground spot of 87774 km2 is about 17,5TW, leading to a massive possible power.

There is no significant difference between a flat and a curved mirror, mainly due to the fact that the spot size is linked to the SPS-Spot distance and not with the size or shape of the mirror:

- The “image” on ground with a (perfectly) flat mirror can be seen as an assembly of multiple cones with a full angle of 0.5° separated by the size of the mirror itself. Considering that in particular the GEO case the size of mirror is much smaller than the size of the cone on ground, it is actually roughly the size of cone on ground, i.e. 0.5°.
- With a curved mirror, the idea is to make all the centroids of the cones to converge, thus “gaining” the size of the mirror on the total spread. But looking at the actual numbers (1m or 1km for a mirror, to be compared with the size of the 0.5° object that is ~300km), is the focusing advantage is negligible.

Any mirror technology is non-compliant with the GEO orbit with ESA requirements

Scenario B & C & D

These scenarios suppose that the SPS is deployed on the 1600 km of altitude, closed to an SSO orbit[2]. Scenario B is based on a multi large mirrors of 1km diameter, D based on small mirrors of 100m diameter and the scenario C a single large:

- In Scenario B, with a 1km diameter mirror, we need 53 single satellites to reach the 1000W/m^2. If they are pointed to a single GPS, they can illuminate 8 minutes at each period. If we want to have a dawn and dusk illumination policy, we need to create a string of 20 clusters, with each composed of 53 single satellites,
- In Scenario C, we have designed the diameter of the mirror for a single large payload, leading to a mirror of 5100m diameter, which seems difficult to deploy.
- In Scenario D, the impact to reduce the diameter of single mirror from 1km to 100m lead to increase the number of SPS per cluster but not the number of cluster (as the illumination period depends mainly on the altitude). Each cluster contains 16976 mirrors of 100m diameter

The Main KPIs are the same (mass launched, number of clusters to get an extended day or Dawn & dusk strategy).

[1] The mass is based on the mirror weight of 20t/km2 (Source : Landis article)

[2] SSO altitudes are 1262 or 1681 km

Scenario D needs 100x the number of mirrors of scenario B because: the difference is mainly due a double effect:
- the size of the mirror : B 1000m vs D 100m
- the orbit altitude : B 890km vs D 1600km

The two factors impact strongly the number of mirrors need to provide 1000W/m2, and we confirm the calculation
The SSO can be a good candidate but the multi small mirrors technology supposes a very large number of single SPS just to reach the minimum irradiance on earth.

Scenario E, F & G

Those ones are based on the same altitude 600km which could be the lowest possible altitude (just 200km above ISS) with single and multi-Small and Large payload technology.
Compared to 1600km, the visibility window is close (before optimization) 4 minutes vs 11 minutes for each rotation. However, the mass to launch is significantly reduced from ~2800t in SSO to ~380t in LEO, that could reduce with the same factor the launching cost and the overall NRC of the program.

But the main shortcoming of this scenario is the **drag force due to residual atmosphere**. It is estimated to 56 mN in the worst case (reflector perpendicular to velocity vector). Considering the relatively very low mass of the reflector, this drag force could alter rapidly the altitude unless using a propulsion subsystem (inducing more mass) to counter this effect.

Several optimizations on the cells of the ground segment could help to reduce the number of SPS, especially adapting the cells to activate below $200W/m^2$ and get a better conversion yield.

Based on this analysis, we could conclude that a 600km altitude orbit could offer the best trade with the multi small mirrors as the most appropriate technology.

Scenario H

To avoid a major drag force, it could however be interesting to increase the altitude, as shown in the table below with an 800 km altitude, where the drag force is estimated to 0.5mM.

Scenario		Multi Small in LEO	Multi Small in LEO
Parameter	**Unit**	**G**	**H**
Orbit altitude	km	600	800
Mirror diameter	m	100	100
Mirror surface	ha	1	1
Results	**Unit**		
Irradiance on Earth	W/m2	0.419	0.236
Visibility window	Min	4	6
Diameter of spot on earth (max)	Km	6	7
Nb SPS to reach 1000W/M2	#	2388	4244
Weight to launch / cluster	t	375	667
Nb of clusters to illuminate 2h	#	29	22
Associated weight to launch	t	10878	14666
Power received in 15km2 before attenuation	GW	15	15
Attenuation due to atmospheric diffusion	%	70%	70%

Table 8 – Sensitivity analysis for two different LEO orbits

Impact of the shaped large mirror in low orbits

A shaped mirror could improve the performance, especially by reducing the spot size, as shown in the table below:

Spread size	1km diameter flat mirror	Curved mirror of focal length 1000km and still 1km in size	Improvement
500km	~4,4 +1km = ~5,4km	~4.9km (4.4+1/2, ½ since the target is at mid-distance of the focal length and that the mirror is 1km in size)	**Improvement of the radiance of +32%** $5.4^2/4.9^2=1.32$
1000km	~8,7 +1km = ~9,7km	~8.7km (8.7+0, 0 since the target is at the focal point of the mirror)	**Improvement of the radiance of 25%** $9.7^2/8.7^2=1.25$

Table 9 – Estimation of the impact of shaped mirrors depending on the orbit distance

If the mirror is smaller than 1km, an improvement is still present but less significant, the level will depend on the actual mirror size. With mirrors of 100m diameter, the impact is almost null, but a cluster of mirrors can be controlled more easily to simulate a curved mirror.

A specific note in annex 1 on the performance of optical systems described in details what could be obtained by several systems.

Based on these scenarios, we decided to assess more deeply the scenario B, for several reasons:
- The expected technology for reflecting mirrors can produce 1km diameter surface, but to go higher can be quite challenging, also for maintaining altitude and beam orientation
- It is better to et a SSO orbit above 800km to avoid any drag effect
- The 890km allows to illuminate a ground plant the same hour of the day, potentially twice a day

5.3 SIZING CASE FOR PAYLOAD TECHNOLOGIES BASED ON DIRECT SUN REFLECTING MIRORS IN LEO ORBIT

The annex 1 describes in detail the process to design the space architecture option concerning DSR. In fact, because each mirror has an angle that vary along the period of visibility window, the preliminary sizing case must be updated. The new space infrastructure design for DSR is based on a train of satellites, each illuminate for during the visibility window with an angle that varies each second. After the visibility window, the satellite changes the beam orientation to the next ground site. The number of satellites in the visibility window is calculated to get 1000W/m2 if irradiance, the global number of satellites is calculated to illuminate a site for 2 hours per day, twice a day.

The case we will focus on is a constellation of 3 152 reflectors of 1 000 m of diameter each, placed on an SSO at 890 km of altitude. SSO at 890 km is convenient for allowing to always have the same local solar time and because 12 hours is a multiple of its orbital period. This makes it possible to extend illumination time of any of the PV farms after sunset and before sunrise each day and therefore making the constellation more profitable (we will see below that unfortunately it was not possible).

This constellation setup allows to have “permanently” 152 scrolling reflectors in visibility of a single ground station with an elevation above 30 deg. Below this elevation the amount of air along the line of sight absorbs too much power. These 152 visible mirrors are all directing their beam towards the same ground station. Clearly, since reflectors are not seen from the ground with the same elevation, each conical beam creates an elliptical spot on the ground. However, in the end this is the superposition of these ellipses which will allow to reach the expected irradiance of 1 000 W/m² in a circular spot of 8.2 km of diameter to feed the PV farm. It means that ideally the PV farm would occupy this entire spot surface.
1 000 W/m² was estimated by Engie to be the good compromise for the PV farm to work efficiently. Below 200 W/m² the PV farm would not be able to produce electricity.
However, the goal of achieving an instantaneous production of 1 000 W/m², is not enough. The final objective is in fact to size the system to produce 750 TWh per year with the SBSP system. We then need to multiply the number of reflectors in orbit and PV farms on Earth.
Consequently, the “train” of reflectors was extended to 3 152 units in order to provide during 2 hours a continuous irradiance of 1 000 W/m² on a given PV farm. Moreover, the number of PV farms was extended to 109 stations (of 8.2 km of diameter each) supposing the system produce 100% of electricity with solar PV. In these conditions, the SBSP could produce yearly 750 TWh.

5.4 SIZING CASE FOR PAYLOAD TECHNOLOGIES BASED ON SOLAR PUMPED LASER

As the TALDA consortium has identified the spot size as the key issue for the DSR performance, its members have tried to find alternative solutions to focus the spot without any active conversion (like what it is done in the RF concept).
Even if this technology has been very recently identified by the consortium and requires further analysis, **we are convinced this technology can be a very promising payload technology option.**

As a summary, a solar pumped laser has the following principles:

- The generation of the solar laser is based on the principle of concentration of sun light in order to **obtain a pumping intensity higher than the threshold necessary to excite the amplifying medium** of the laser system.
- For this purpose, optical concentrating devices are used as the primary stage such as the concentrator three-dimensional parabolic, the spherical concentrator, the Fresnel lens, etc.
- Gases, liquids and solids are all considered candidates for amplifying media laser systems. **Solid lasers seem to be the most attractive for solar pumping** due to their high density of energy and to be compact, their relatively low pumping threshold and their efficiency potential energy conversion: solar / laser.
- Photovoltaic technologies, laser diodes and pumped solid state lasers laser diode have attracted great attention in the past and have achieved maturity and efficiency for important industries. Sunlight can illuminate photovoltaic cells to produce electrical energy which powers the laser diodes. The laser light emitted can pump a solid laser. This method is called indirect pumping which can be applied for DSR as it supposes an active conversion.
- **Direct pumping of solid-state lasers by concentrated sunlight** saves two stages of energy conversion, which allows them to be more efficient, simpler and more reliable. However, less attention has been devoted to direct solar pumped lasers and therefore the technology is currently less mature.

A simple sizing case demonstrates the breakthrough benefits of this technology:

Parameter	Value	Unit	Comment
Sun Power density on Earth orbit	1361	W/m²	Received on the reflector
Reflector diameter	1000	m	Input
Reflector surface	785,398	m²	
Power conversion efficiency	5	%	4,64% up to 8% depending on the paper
Laser input power	1,068,926,900	W	
Laser output power	53446345	W	
Power to dissipate	1,015,480,555	W	Need to control temperature to keep yield ratio
Laser pump min diameter	0.30	m	Possible ?
Laser wavelenght	1064	nm	So far 1064 and 1310 nm tested - 1064 is infrared so not visible
Atmospheric absorption @ wavelength	92.4	%	To be checked
Laser divergence half-angle	2	µrad	Check if we have to consider the pump min radius or another min radius of the apparatus
Laser altitude	36000	km	GEO is the best orbit but the most complex for limiting the spot size
Laser spot diameter on ground	**163**	**m**	
Total laser power in the spot	49,384,423	W	Output power x absorption
Power density in the spot	**2379**	**W/m²**	
Weight / SPS	25	t	
Nb of Pumped Laser to get 1GW	21	#	
Total weight	**528**	**t**	
Energy produced	303	GWh	
Nb of SPL to prodice 750TWh	**2,477**	#	

Table 10 – Model of the sizing case for the Solar Pumped Laser Payload technology

With a reflector of 1000m located in a GEO orbit and (although a 5% of conversion rate), it is possible to target a spot size of 163m diameter with a intensity comparable to the natural sun (2379W/m^2 at a single wavelength), therefore:

- It seems possible to get a very located spot size, even in an GEO orbit
- It seems possible to transmit enough intensity to create a spot size equivalent to a second artificial sun, even during night
- The light transmitted has a single wavelength, allowing to adapt the PV cells to maximize their yield conversion at this value
- This performance could be obtained with a rather small single SPS (1000m of diameter), so easy to launch and assembly

The evaluation of the payload technology can now be updated with the solar pumped laser, showing its clear leadership compared to the others:

0 Not performant
5 Very good performance

Payload technology	Assumption of the reflector dimension	Techno accessibility	Power provided in a 15km2 area	Spot size in GEO	Spot size in SSO	Light pollution	Altitude control	Scalability	Complexity of deployment in space	Launching complexity	Targeting ground segment	Evaluation note
Criteria weight		2	3	1	2	2	2	3	2	1	2	20
Multi Small Mirrors	Diameter 100m	5	2	0	1	1	4	4	4	4	3	58
Multi Large Mirrors	Diameter 1km	3	2	0	2	3	3	3	2	3	3	50
Single Large Flat Mirror	Diameter >>1km	2	1	0	1	1	1	1	1	1	1	21
Single Large Shaped Mirror (parabolic)	Diameter >>1km	1	2	0	2	1	1	1	1	1	1	24
Solar pumped Laser	Diameter 1000m	3	4	4	4	4	4	4	2	3	4	73

Table 11 – Comparison of the different payload technologies

Even if this technology offers significant benefits, several issues have to be investigated:

- If it has already been demonstrated in laboratory, is it possible to deploy a full scale version with a large laser pump?
- How can the system be managed to control the system temperature and/or light pollution to acceptable levels
- What could be the environmental impact on the atmosphere with this IR energy?
- What could the optimal design of the tube to maximize the conversion ratio and minimize the weight?

6. ARCHITECTURE PRE-SELECTION

Based on the previous analysis, two main architectures present some promising results :

Parameter	Architecture DSR	Architecture SPL
Orbit altitude	890 km (LEO)	36 000km (GEO)
Orbit inclination	I°	0°
Payload technology	Direct Sun Reflecting with Multi Large mirrors	Solar Pumped Laser
Final Output	Solar Molecules and / or PV in Europe (tbd)	Electricity mainly but could be deployed for solar molecules
Location of the GPS plant	Near the equator in desert or Off shore Europe + outside Europe	Mainly Europe but possible elsewhere
Power range / GPS	5GW ideally and no more than 1GW on-grid	< 1GW ideally for electricity
Illumination period	Extended day (depending the LCOE and the environmental impact)	24/7

Table 12 – Key elements of the two architecture options to be further analyzed

The preferred end-of-life strategy (Design for recycling/refurbishing) will be compliant with current (and near future) and no roadblocks have been identified in applying this strategy. However, several strategies should be used to manage the end of life requirement with no debris.

Each candidate will be assessed according several parameters:

Criteria	KPI
Cost	LCOE
Energy expenditure	ERoEI across the system lifetime
Global energy to provide	Feasibility to deliver 750 TWh in 2050 (Nb of plants needed)
Environmental impact	First estimation of the preliminary environmental impact on key modules
Scalability and industrial capability	Accessibility to industrial assets to deploy full scale architecture
Technology maturity	Range of investment to target at least TRL 5 in 2030
Risk	Probability of failure, total/partial outage of the system, impact of specific failures

Table 13 - Criteria used to select the reference architecture

Those criteria will be used to select the final reference architecture.

In addition, a more detailed description will be done to optimize the key parameters of each candidate, even if the task 4 and 5 will be dedicated to define more deeply these optimizations.

7. ARCHITECTURE PRUNING

7.1 INTRODUCTION

Solutions have to be found for the part of the system in space but also for the part on the ground. In space, two main options can be considered: the first is direct sun reflection, where we make solar rays change direction to direct them towards energy producing solutions on Earth. The second is one where we concentrate rays on a system that produces coherent light rays.
On the ground, four technical options can be considered : the first half produces electricity - the solar photovoltaic panel and the wavelength adapted solar PV. The second half produces hydrogen: the solar photovoltaic panel that feeds an electrolyser, and the solar fuel cell.

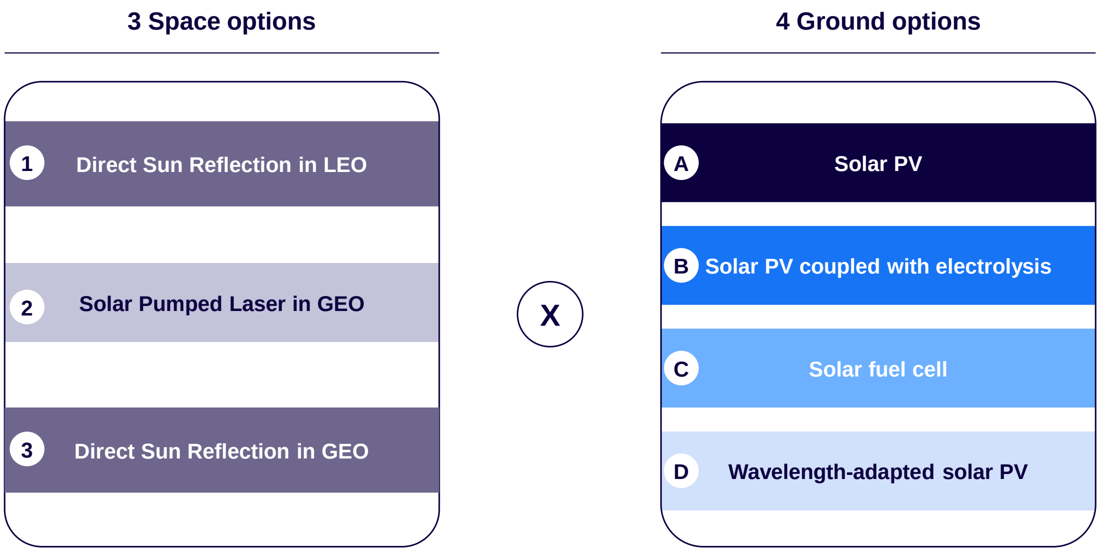

Figure 1 - options in space and on the ground for designing the reference architecture

Each option will be described in the following paragraphs.

7.2 SPACE INFRASTRUCTURE ARCHITECTURE

Both technical possibilities are described within the configurations found in the previous part of the document. Key elements may vary with previous findings as models and simulation are further refined.

7.2.1 DIRECT SUN REFLECTION

The principle is to send systems composed of lenses, reflectors and mirror to divert solar rays in the direction we want. Here is an optimal example of this system to illustrate its way of working:
3,152 satellite are evenly placed in a sun-synchronous orbit around Earth, at about 890km. Each satellite carries a round reflector with a diameter of 1km which it can rotate. A group of satellites flying over a ground station can then rotate its reflectors in order to send solar rays towards it. It produces a spot of light on Earth with a diameter of 8.3km which is composed of rays from 152 satellites above it.

The satellites which are below 30 degrees above the horizon rotate to send their solar beam on other ground stations as the light would be dissipated to much in the atmosphere. Because the satellites are in movement compared to the ground stations, they continuously rotate their reflectors to aim towards the plant. When they get below 30 degrees inclination, they change target.

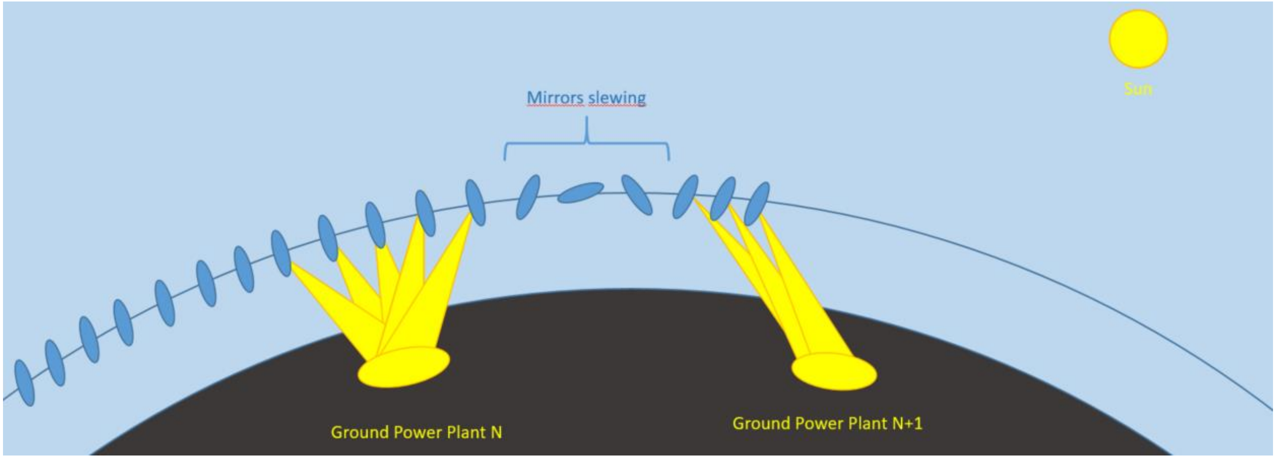

Figure 2 - Schema of DSR architecture

As previously said, the aim to produce 1000W/m on Earth produced a series of issues. In order to do so, the mirror has to be quite big if we don't want to have to many satellites. It was quickly discovered that because of that, the spot size created on Earth was very big. And, the further away from Earth the satellite is, the bigger the spot size, the bigger the power dissipation is: to achieve 1,000W/m^2 more reflective surface is needed. It can be done with more satellites or bigger mirrors. There is a direct correlation, as described in this graph.

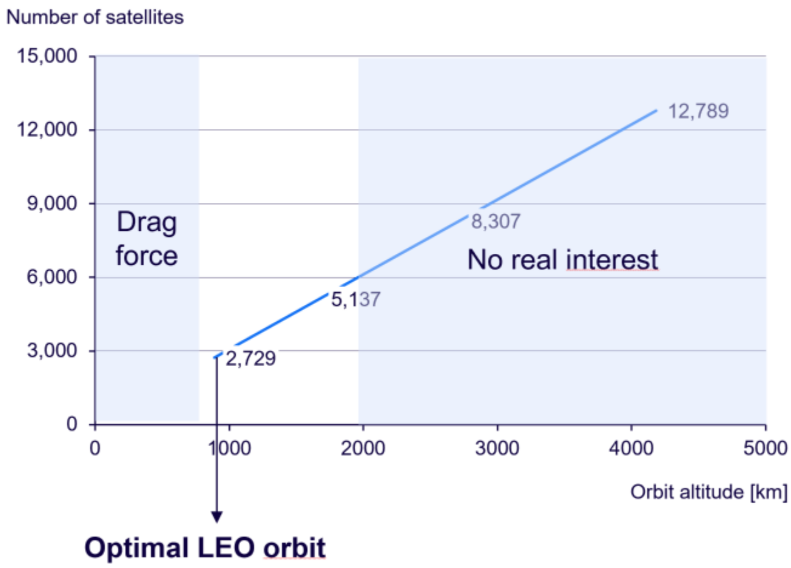

Figure 3 - Number of 1km diameter satellites for an orbit to reach 1000W/m2 on Earth

Faced with this problem, multiple technical solutions – detailed in TN2-Annex1 – were considered in order to reduce the spot size on Earth. Some of which are combinations of lenses, mirrors and reflectors. Other are another type of technical solutions in in of itself.

7.2.2 SOLAR PUMPED LASER

In this case, 2,889 satellites are evenly spaced in a Geostationary orbit at 36,000km. Each satellite carries a reflector of 1,000m diameter which redirects light beams towards the pumping cavity. It then sends a laser towards earth which produces a spot on Earth with a diameter of 163m. The irradiance is up to 2,400W/m^2 on 2889 ground stations (or less). This produces an equivalent spot size with a diameter of 9km.

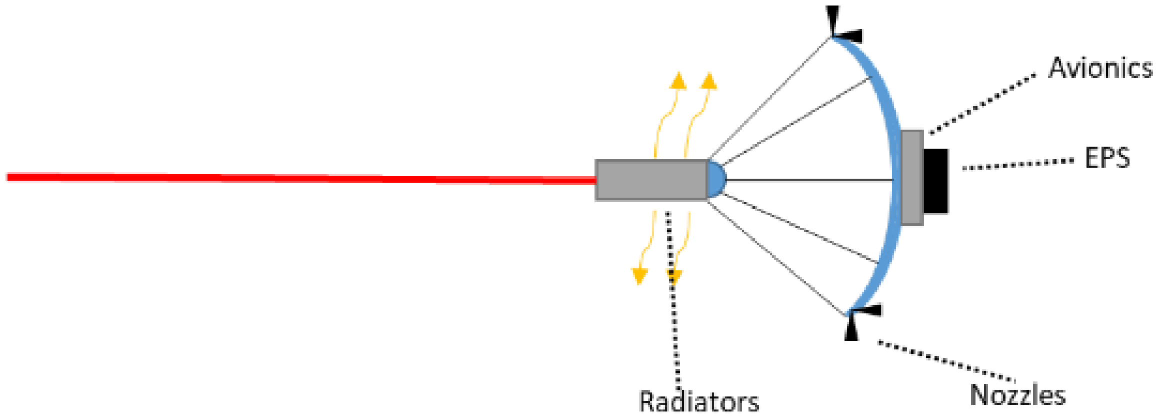

Figure 4 - simple representation of solar pump laser

One the characteristics of the coherent light beam can be here observed: because it is very concentrated, its irradiance (function of power over surface) can easily get higher than 1,000W/m^2. A solution to dissipate the beam was sought. It was found that a telescope could be placed right after the pumping cavity. It can be scaled depending on the scale of the main reflector in order to produce an exit beam with an irradiance no higher than 1,000W/m^2.

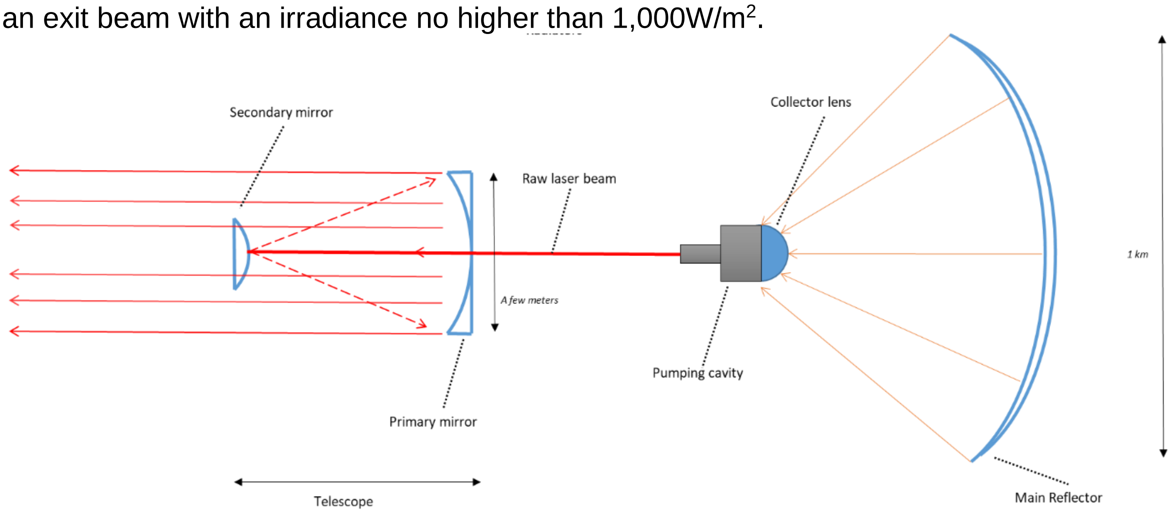

Figure 5 - simple representation of solar pump laser with divergent lens

Please note that the Irradiance of the exit beam is also dependant of the main reflector size. The latter could be reduced in order to achieve 1,000W/m^2. However in this case, more satellites would be needed in the constellation in order to reach a 750TWh yearly production. Thus, it is here preferred to collect the most amount of power possible and then dissipate it to acceptable levels. It implies higher surface collectors on the ground, but this is deemed more feasible than more satellites on orbit.

Finally, radiators will be needed to cool down the centre piece of the laser. Their scale will be calculated in the next step of the project if this solution is chosen.

7.2.3 COMPARISON

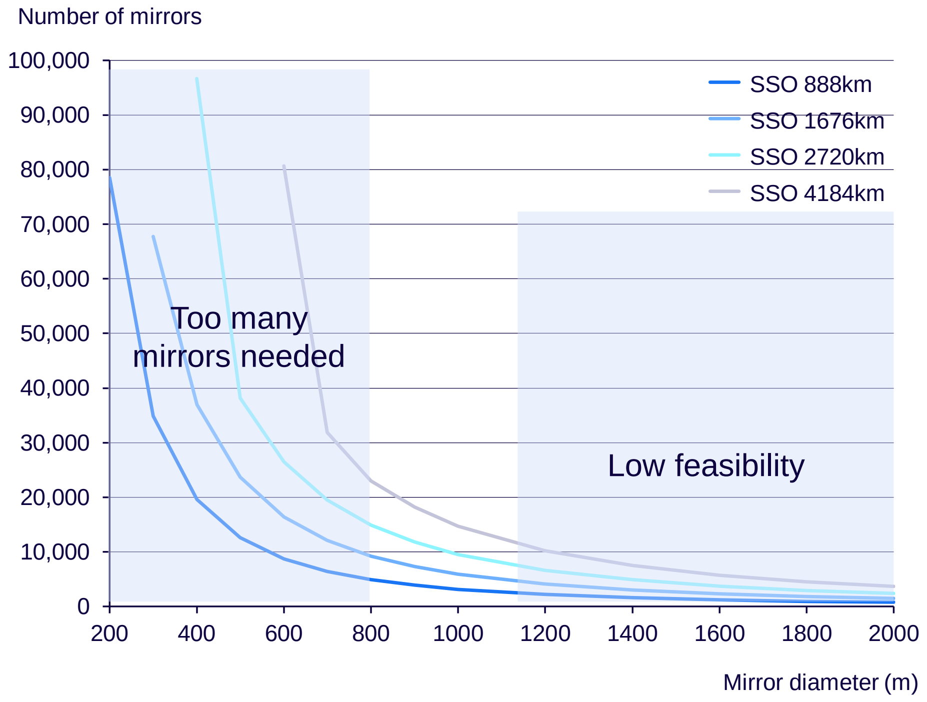

Figure 6 - Number of reflectors needed to reach 1000W/m2, depending on mirror diameter

As a reminder: both solutions have 1km diameter reflectors. Direct sunlight reflection are placed in Low Earth Orbit at around 890km. Solar pumped laser are placed in geostationary orbit at around 36,000km. The aim for both is to produce 750TWh of electricity yearly and respect the requirements.

Here the synthesis of this comparison:

	LEO DSR	GEO SPL
Number of platforms	2'729	1'445
System complexity	"Simple" large focusing reflectors	Large focusing reflectors + collector + laser pumping + télescope
	Complex slew capability	Steady pointing
Launches	5'044 A6 or 1'225 Starship (resp. 97 and 24 years with 1 launch/week)	5'161 A6 or 1'806 Starship+spacetruck (resp. 99 and 35 years with 1 launch/week)
Min number of ground power units	109 stations geographically separated	Very flexible: 1 big to 1'445 small
Availability	+2 x 2h/day	24/7
Ground footprint	584 000 ha	3 000 ha
Environmental effects	Large elliptical spots wasting power outside of the core spot	Small circular beams
	Visible trails of hundreds of satellites (in LEO) 2h after sunset	Very small if not invisible
	Visible reflected beam	Beam invisible (NIR)
Yearly station keeping fuel cost per unit	540 kg	80 kg
Potential techno/performance increase	Limited	Promising
Reuse existing PV farms	Yes	Yes

Table 14 - architecture comparison synthesis

Here, it is confirmed **the solar pumped laser is more promising**. It is, on almost all aspects, more advantageous. On the ground, it enables for less infrastructure, smaller beams and less environmental impact (ground and visible footprint). However, its system in space complexity is higher, at least for each space unit. Whereas only reflectors are needed for the direct sunlight reflection solution, collectors and laser pumping devices and telescope are needed for the solar pumped laser.

Please note that as of today, most of the PV farms have silicon PV panels, that can accept 1064nm irradiance, with a lower conversion ratio, estimated by ENGIE around 10%. Also, new emerging technologies of PV panels based on perovskite solar cells could be used in the coming decades, with a limitation that this technology do not accept today 1064nm wavelength. However, we consider this technology will be deployed not before 2030 and the conversion of the PV farm stock will take at least 30 years to be complete. During this period and if the SBSP infrastructure is deployed and competitive, specific perovskite-PV panels accepting 1064nm could be commercialized.

7.3 GROUND INFRASTRUCTURE ARCHITECTURE

7.3.1 FOUR GROUND-BASED ENERGY PRODUCTION SYSTEMS COMPARED

On the ground, four technical options can be considered : the first half produces electricity - the solar photovoltaic panel and the wavelength adapted solar PV. The second half produces hydrogen: the solar photovoltaic panel that feeds an electrolyser, and the solar fuel cell.

Here is the synthesis of each technology, especially in terms of yield rate :

Efficiency	Solar PV	Solar PV + Electrolysis	Solar Fuel Cell	Wavelength-adapted panel
DSR	25%	12.5%	40%	n.a.
SPL	25%	12.5%	40%	60%

Figure 7 – Ground based energy production systems specifications comparison - Yield

As the laser produces a light beam on a specific wavelength, laser beams are transformed in electricity a little less efficiently than light beams, but their power is less dissipated by the atmosphere when coming down from space. So, when all things are considered: traditional systems produce energy with laser beams with the same efficiency as light beams.
However, solar panels adapted to best absorb light at laser's specific wavelength have to be developed. And they are expected to present a ratio of converting laser to electricity with an efficiency of 60%[3]. Light will only be converted with an efficiency of 10%.

The solar fuel cell seems to be the more complete solution with 40% efficiency in converting light or laser beams in hydrogen. And the wavelength adapted panel shows the best efficiency, at 60% for converting laser beams in electricity.

Please note that, after consultation with ENGIE experts on the matter, weather and filling of the plant were considered in our computations in order to be complete. These take into account that sometimes, clouds or other meteorological phenomenon will hinder overall system efficiency. And that on a given surface, panel don't cover all of it because of holes, cables or equipment passing through.

	Solar PV	Solar PV + Electrolysis	Solar Fuel Cell	Wavelength-adapted panel
CAPEX (€/kWp)	320	740	480	480
OPEX (€/kWp/y)	5.0	7.3	7.5	5.0

Figure 8 - Ground based energy production systems specifications comparison - Cost

Traditional solar panels present an efficiency in the middle range, but the best CAPEX and OPEX overall.
Traditional photovoltaic panels coupled with electrolysers really come as the worst solution presenting both the worst efficiency and financials.
Solar fuel cell, the most complete solution in regards to efficiency presents highest OPEX coming 50% higher than traditional solar panels and wavelength adapted panel. The same is true for their CAPEX coming in 50% higher compared to traditional solar panels.

[3] Source : Astrium, Engie

Finally, wavelength adapted panel which presented the highest efficiency – with laser beams – have the same CAPEX with solar fuel cells and the same OPEX as traditional solar panels[4].

7.3.2 FOCUS ON DSR ARCHITECTURE AND IMPACT

With sun synchronous low earth orbits, flybys over multiple sites on Earth occur. In order to answer the question, 11 sites have been identified as archetypes for the global group needed. The LEO orbit allows to scale up to 90 sites around the world.

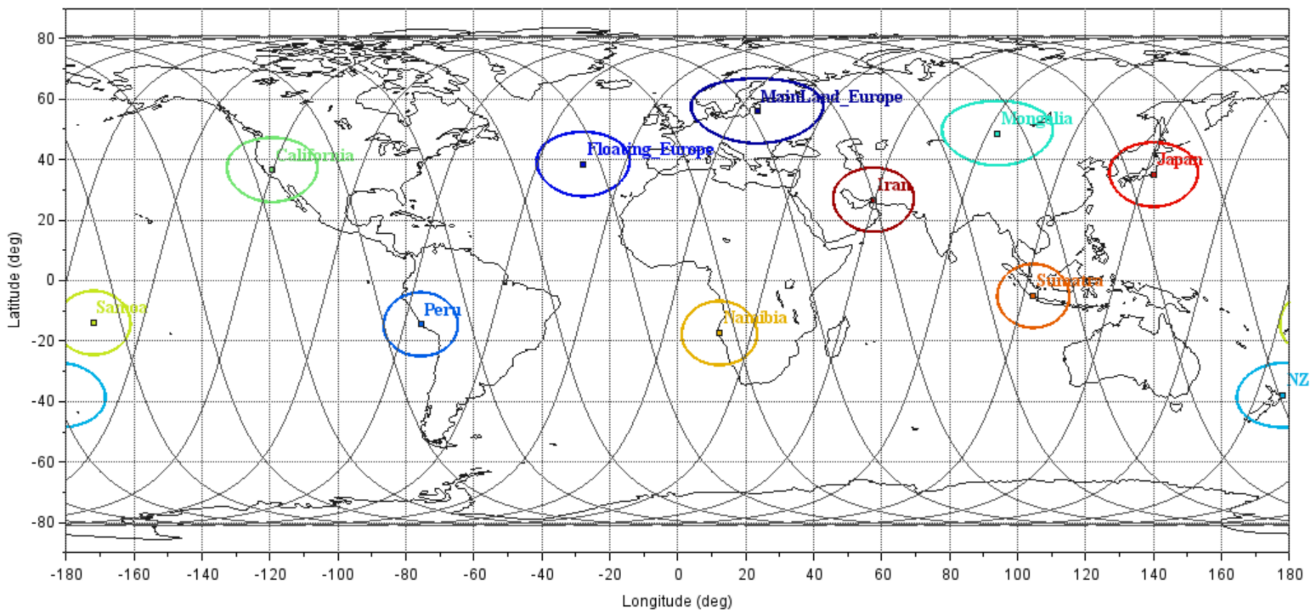

Figure 9 - Localization of the 11 site archetypes

Multiple latitude were considered to take seasonality into account and its effect on production. This also allows for various weather types. ENGIE experts then computed yield with sun and mirror (which includes production that would occur without the space constellation with the production added by the space constellation), and yield with mirror only (which only includes the production brought by the space constellation). Computation considered that the space constellation would bring 2h of 1,000W/m^2 twice a day.

To estimate the extra energy resulting from the train of satellites redirecting light onto the power plants located at the earth's surface, a number of assumptions have been made. The assumptions are roughly a first approximation for the positioning of the satellites and the energy intensity that can be expected

- Position of the energy source is assumed to be at the zenith
- The extraterrestrial light intensity is equivalent to a constant 1000 W/m²
- Each site receives the light from the satellite train for 2 hours every 12 hours, assumed to be from 7 AM-9 AM and 7 PM-9 PM according to the local time zone.

The tested PV set-up is for a very dense layout where modules are in an east-west disposition. Several angles for the tilt have been tested between 0° and 15°, to find the optimal angle for each location. The proposed coverage ratio used in the simulations is 0.9.

[4] Source : Engie experts

The received light from the satellites is affected by the local meteorological conditions. This is estimated using the data from the typical meteorological year of the site. A clear-sky index is calculated for each day, using the ratio of the global received irradiance from the sun for that day and the expected irradiance one would have on a day with a clear sky. The clear-sky index is a correction factor for the intensity of the light that is reaching the earth's surface for that specific day. The simulated extra yield resulting from the light redirected by the satellites could strongly depend on the assumptions and method used for the attenuation by the local conditions. The results presented next are therefore subject to changes.

Simulation	Use-case	Coordinates	Location	Year-average clear-sky index[1]	Yield sun only [kWh/kWp.yr]	Yield mirror [kWh/kWp.yr]	Yield sun & mirror [kWh/kWp.yr]	% Gain
A	Mainland Europe	56.24N, 23.30E	Lithuania	60.8%	892	899	1,791	>100%
B	Floating Europe	38.64N, 27.9W	Azores	53.4%	1,042	762	1,804	73%
C	Mainland non-Europe	14.46S, 75.7W	Peru	90.3%	2,147	1,271	3,419	59%
D	Floating non-Europe	38.0S, 178E	N-Z	68.0%	1,425	991	2,416	70%
E	Mainland non-Europe	48.86N, 94.0E	Mongolia	66.2%	1,321	979	2,300	74%
F	Mainland non-Europe	30.39N, 115.76W	California	86.6%	1,889	1,227	3,116	65%
G	Floating non-Europe	14.0S, 172.0W	Samoa	76.6%	1,787	1,048	2,835	59%
H	Mainland non-Europe	17.38S, 12.2E	Namibia	97.2%	2,268	1,340	3,608	59%
I	Mainland non-Europe	5.05S, 104.57E	Sumatra	68.8%	1,613	954	2,568	59%
J	Floating non-Europe	35.19N, 140E	Japan	67.9%	1,401	972	2,373	69%
K	Mainland non-Europe	26.84N, 57.56E	Iran	90.2%	1,897	1,227	3,124	65%
TOTAL (TWh/y for 1GWp)					17,682		29,354	

+ 66%

Note: 1) index is average sky coverage because of clouds, 100% meaning no clouds
Source: Engie, Arthur D. Little

Figure 10 – Impact of the space infrastructure on 11 terrestrial site archetypes (Source : Engie)

The total yield, under the current assumptions, is composed of around 50% of natural energy yield, and a significant contribution of 50% from the light of the mirrors. The added value of the constellation appears here. In every case, no matter the latitude or position on Earth, production of energy is more than 66% on average when the space constellation is taken into account.

Difference in yield depending on latitude in also clearly visible both for sun and mirror, and mirror only. When considering sites of 1 GWp on these 11 locations, the expected DC yield is 29.35 TWh. The estimated area of such a site of 1 GWp is of 444 ha.

In order to scale the expected yield to the order of 750 TWh, the PV arrays or the yield needs to be scaled up. There are mainly two ways to scale up the production, when considering the same type of satellites and orbits (without modification of the assumptions of the energy contribution). The first way would be to increase the number of generation sites in the world. However, the number of sites the satellite train can be redirected to along its synchronous orbit is limited. Alternatively, the size of each site could be scaled to become significantly larger, bringing however other challenges related to operations, management, interconnection or energy storage costs.

7.4 SCENARIO COMPUTATION

7.4.1 DESCRIPTION OF SCENARIOS

We enumerate five scenarios each taking a clear lean towards a set of solutions. This enables for a better overview of what each brings . Once these are compared and the best configurations are identified, the inputs will be affined.

Scenario	Space: Technology and orbit	Ground: Europe	Ground: Rest of World
1	DSR in LEO[1]	**36** (20%) existing solar PV plant	**145** (80%) new solar PV + electrolysis plants
2	DSR in LEO[1]	**15** (20%) existing solar PV plants	**59** solar fuel cell plants
3	SPL in GEO[2]	**58**[3] existing solar PV plants	*None*
4	SPL in GEO[2]	**24**[3] wavelength-adapted solar PV plants	*None*
5	DSR in GEO[2]	*None*	**1** site producing H2 with solar fuel cell plants

Figure 11 -Scenarios considered in analysis

Then, regarding the ground segment we form two parts: Europe and the rest of the word. Here, various combinations of the possible ground solutions are formed.
Please note that the spot created by the satellites provides power such that the solar panels deliver output power close to 10GW, assuming they cover the entire spot size. The number of stations in Europe shown corresponds to stations with these power levels. For the future, we'll need to reduce the surface area of stations in Europe to meet network constraints and/or provide energy storage capacity to limit output power and/or increase the number of stations outside Europe to reach 750TWh if necessary. This detailed analysis will be carried out once the architecture has been selected, but will have only a minor impact on the estimated KPIs.

7.4.2 RESULTS OF COMPUTATION

A selection of the most important criteria was aggregated in this table with more details in appendix of the document. It covers all aspects of the project: financials, energy, carbon footprint, technical feasibility, industrial scalability. This gives a good idea of each scenario’s strength and weaknesses.

Main KPIs for the five scenarios considered
Space only / Space + New ground

	1	2	3	4	5
LCOE *c€/kW*	18.0 / 38.5	18.0 / 17.8	12.6 / 12.6	2.6 / 3.0	0.2 / 0.2
Carbon intensity *$gCO_{2,eq}$/kWh*	4 / 29	4 / 12	4 / 4	4 / 5	<1
EROI	112x / 15x	112x / 36x	109x	111x / 92x	>3'000x
# launches	1'225		1'806	753	36'841
Mass in orbit *kton*	86		36	15	2'579
CAPEX system *€bn – Space / Ground*	654 S + 1189 G	753 S + 313 G	279 S	116 S + 16 G	19'669 S + 298 G
Net avoided emissions[1] *$MtCO_{2,eq}$ over 30y*	9'566 / 13'742	9'566 / 15'781	9'564	9'566 / 9'586	9'888'774
Scalability & capability					
Technology maturity					
Low-risk					

Table 15 - main KPIs for the five scenarios

Please note that direct Orbit injection is considered (no tug). Space tug in standard chemical propulsion would not be more interesting. Electrical or Hydrogen tugs could be an alternative but with impact on transfer duration (electric) or on TRL (hydrogen).

GEO Solar Pumped Laser seems to be the most appealing for most of the criteria

- It offer the **best compromise LCOE/EROI/CO2Impact**, especially with adapted panels
- It offers the **best potential of improvement** due to the maturity increase to be done for SPL
  - For example, for the space segment, experts do believe that in a decade **10% of efficiency could be reached in solar pumping laser**, while we considered 5% as of today.
  - In the same way, we considered modified **PV farms on the ground with limited irradiance** while other technologies like thermal solar panels could be more efficient at higher irradiance.
- Its two main shortcomings are
  - the **launch solutions** which are far from compliant with the overall mass to place in GEO (but this is also true for LEO DSR)
  - the **lack of analysis in making solar pumped lasers** in space as far as we have seen in the bibliography.
  - the maturity of the technology could **impact the time to market** for more than 2030

DSR in LEO with a majority of solar fuel panels producing H2 is a good alternative

- Its **LCOE is closed to SPL in GEO** but EROI and CO2 impact is roughly 40% less than SPL in GEO
- It offers of **good alternative with most existing space technologies with a possible time to market in 2030**
- However it main shortcomings are :
  - A **challenging complexity in operations** to manage altitude and beam orientation in real time more than 3000 space units and synchronize them all over the world

- **Finding more than 100 plants of >8km2 along the trajectory could be challenging** to reach 750TWh or equivalent
- the **launch solutions** which are far from compliant with the overall mass to place in GEO (but this is also true for LEO DSR)

APPENDIX : DETAILED ANALYSIS OF ARCHITECTURE SCENARIOS

5 categories of KPI are formed in two groups: space and ground settings, and outputs. The first category lists the inputs and implications for the constellation. The second lists the implications for the satellite itself and the number of stations. Then three categories list financials, energy and carbon related metrics.

Scenario 1 – DSR LEO PV + PV & Electrolysis: Detailed KPIs

PRELIMINARY

Space and ground settings

Technology	DSR	Mass in orbit	43kt
Orbit	LEO 890km	# of launches	613

Time to launch all satellites fixed to 20 years

# reflectors	2'730	Reflectors diameter	1km
Spot diameter	8.3km	# of ground stations	181

Scalability | Technology maturity | Risks

36 existing PV plants in Europe

145 new PV + electrolysis plants outside Europe

Main outputs

Financials (€bn)

CAPEX space	327	LCOE - Space only (c€/kWh)	8.2
CAPEX ground	1'189	LCOE - New infra[1] (c€/kWh)	29
Annual OPEX	12		

Energy (TWh/y elec / TWh/y H2)

Produced - Space	250 / 500	Prod. Mt H2/y Space	8.3
Produced - New infra[1]	250 / 894	Prod. Mt H2/y New infr	14.9
Produced - Exist. infra	197		
		EROI - Space only	612x
		EROI - New infra[1]	16x

Carbon (CO2eq (over 30 years))

Intensity - Space	0.7g/kWh	Net avoided[2] - Space	9'637Mt
Intensity - New infra[1]	26g/kWh	Net avoided[2] - New inf	13'812Mt

Table 16 - scenario 1 KPIs

Scenario 2 – DSR LEO PV + Solar fuel cell: Detailed KPIs

PRELIMINARY

Space and ground settings

Technology	DSR	Mass in orbit	43kt
Orbit	LEO 890km	# of launches	613

Time to launch all satellites fixed to 20 years

# reflectors	2'730	Reflectors diameter	1km
Spot diameter	8.3km	# of ground stations	74

Scalability | Technology maturity | Risks

15 existing PV plants in Europe (8km diameter)

59 new solar fuel cell plants outside Europe (8km diameter)

Main outputs

Financials (€bn)

CAPEX space	327
CAPEX ground	313
Annual OPEX	5.2

c€/kWh	
LCOE - Space only	0.7
LCOE - New infra[1]	10

Energy (TWh/y elec / TWh/y H2)

Produced - Space	101 / 649
Produced - New infra[1]	101 / 1'160
Produced - Exist. infra	80

Prod. Mt H2/y Space	10.8
Prod. Mt H2/y New infr	19.3
EROI - Space only	612x
EROI - New infra[1]	43x

Carbon (CO2eq (over 30 years))

Intensity - Space	0.7g/kWh
Intensity - New infra[1]	10g/kWh

Net avoided[2] - Space	9'641Mt
Net avoided[2] - New inf	15'858Mt

Table 17 - scenario 2 KPIs

Scenario 3a – GEO SPL + Solar PV: Detailed KPIs

PRELIMINARY

Space and ground settings

Technology	SPL	Mass in orbit	214kt
Orbit	GEO 36'000km	# of launches	10'701

Time to launch all satellites fixed to 20 years

# reflectors	40'810	Reflectors diameter	458m
Spot diameter	163m (~2ha)	# of ground stations	1'625

Scalability | Technology maturity | Risks

1'625 existing solar PV plants of 50ha each in Europe

Main outputs

Financials (€bn)

CAPEX space	1'632
CAPEX ground	0
Annual OPEX	7.5€m

c€/kWh	
LCOE - Space only	41
LCOE - New infra[1]	41

Energy (TWh/y elec / TWh/y H2)

Produced - Space	750 / 0
Produced - New infra[1]	750 / 0
Produced - Exist. infra	85

Prod. Mt H2/y Space	0
Prod. Mt H2/y New infr	0
EROI - Space only	42x
EROI - New infra[1]	42x

Carbon (CO2eq (over 30 years))

Intensity - Space	10g/kWh
Intensity - New infra[1]	10g/kWh

Net avoided[2] - Space	9'421Mt
Net avoided[2] - New inf	9'421Mt

Table 18 - scenario 3a KPIs

Scenario 3b – GEO SPL + Solar PV: Detailed KPIs

PRELIMINARY

Space and ground settings

Technology	SPL	Mass in orbit	214kt
Orbit	GEO 36'000km	# of launches	10'701
# reflectors	16'982	Reflectors diameter	710m
Spot diameter	163m (~2ha)	# of ground stations	679

Time to launch all satellites fixed to 20 years

Scalability · Technology maturity · Risks

679 existing solar PV plants of 50ha each in Europe

Main outputs

Financials (€bn; c€/kWh)

CAPEX space	1'639	LCOE - Space only	41
CAPEX ground	0	LCOE - New infra[1]	41
Annual OPEX	7.5€m		

Energy (TWh/y elec / TWh/y H2)

Produced - Space	750 / 0	Prod. Mt H2/y Space	0
Produced - New infra[1]	750 / 0	Prod. Mt H2/y New infr	0
Produced - Exist. infra	35.7 / 0		
		EROI - Space only	42x
		EROI - New infra[1]	42x

Carbon (CO2eq (over 30 years))

Intensity - Space	10g/kWh	Net avoided[2] - Space	9'421Mt
Intensity - New infra[1]	10g/kWh	Net avoided[2] - New inf	9'421Mt

Table 19 – scenario 3b KPIs

Scenario 4a – GEO SPL + Adapted solar PV: Detailed KPIs

PRELIMINARY

Space and ground settings

Technology	SPL	Mass in orbit	89kt
Orbit	GEO 36'000km	# of launches	4'459
# reflectors	17'004	Reflectors diameter	458m
Spot diameter	163m (~2ha)	# of ground stations	677

Time to launch all satellites fixed to 20 years

Scalability · Technology maturity · Risks

677 adapted solar PV plants of 50ha each in Europe

Main outputs

Financials (€bn; c€/kWh)

CAPEX space	680	LCOE - Space only	17
CAPEX ground	40	LCOE - New infra[1]	16
Annual OPEX	447€m		

Energy (TWh/y elec / TWh/y H2)

Produced - Space	750 / 0	Prod. Mt H2/y Space	0
Produced - New infra[1]	835 / 0	Prod. Mt H2/y New infr	0
Produced - Exist. infra	0 / 0		
		EROI - Space only	100x
		EROI - New infra[1]	75x

Carbon (CO2eq (over 30 years))

Intensity - Space	4.3g/kWh	Net avoided[2] - Space	9'556Mt
Intensity - New infra[1]	5.7g/kWh	Net avoided[2] - New inf	10'608Mt

Table 20 - scenario 4a KPIs

Scenario 4b – GEO SPL + adapted solar PV: Detailed KPIs

PRELIMINARY

Space and ground settings

Technology	SPL	Mass in orbit	89kt
Orbit	GEO 36'000km	# of launches	4'459

Time to launch all satellites fixed to 20 years

# reflectors	7'076	Reflectors diameter	710m
Spot diameter	163m (~2ha)	# of ground stations	283

Scalability | Technology maturity | Risks

283 adapted solar PV plants of 50ha each in Europe

Main outputs

Financials (€bn; c€/kWh)

CAPEX space	683	LCOE - Space only	17
CAPEX ground	40	LCOE - New infra[1]	17
Annual OPEX	447€m		

Energy (TWh/y elec / TWh/y H2)

Produced - Space	750 / 0	Prod. Mt H2/y Space	0
Produced - New infra[1]	786 / 0	Prod. Mt H2/y New infr	0
Produced - Exist. infra	0 / 0		
		EROI - Space only	100x
		EROI - New infra[1]	71x

Carbon (CO2eq (over 30 years))

Intensity - Space	4.3g/kWh	Net avoided[2] - Space	9'556Mt
Intensity - New infra[1]	6.1g/kWh	Net avoided[2] - New inf	9'969Mt

Table 21 - scenario 4b KPIs

Scenario 5 – DSR LEO 100% existing solar PV: detailed KPIs

PRELIMINARY

Space and ground settings

Technology	DSR	Mass in orbit	43kt
Orbit	LEO 890km	# of launches	613

Time to launch all satellites fixed to 20 years

# reflectors	2'730	Reflectors diameter	1km
Spot diameter	8.3km	# of ground stations	109

Scalability | Technology maturity | Risks

109 existing PV plants in or out Europe (8km diameter)

No new PV plants (8km diameter)

Main outputs

Financials (€bn; c€/kWh)

CAPEX space	327	LCOE - Space only	8.2
CAPEX ground	0	LCOE - New infra[1]	8.2
Annual OPEX	7.5€m		

Energy (TWh/y elec / TWh/y H2)

Produced - Space	750 / 0	Prod. Mt H2/y Space	0
Produced - New infra[1]	750 / 0	Prod. Mt H2/y New infr	0
Produced - Exist. infra	591 / 0		
		EROI - Space only	612x
		EROI - New infra[1]	612x

Carbon (CO2eq (over 30 years))

Intensity - Space	0.7g/kWh	Net avoided[2] - Space	9'637Mt
Intensity - New infra[1]	0.7g/kWh	Net avoided[2] - New inf	9'637Mt

Table 22 - scenario 5 KPIs

Scenario 5bis – DSR LEO 20% existing solar PV and 80% new solar PV: detailed KPIs

PRELIMINARY

Space and ground settings

Technology	DSR	Mass in orbit	43kt
Orbit	LEO 890km	# of launches	613

Time to launch all satellites fixed to 20 years

# reflectors	2'730	Reflectors diameter	1km
Spot diameter	8.3km	# of ground stations	917

Scalability | Technology maturity | Risks

240 existing PV plants in Europe (50ha)

917 new solar PV plants (50ha)

Main outputs

Financials €bn

CAPEX space	327	LCOE - Space only (c€/kWh)	8.2
CAPEX ground	308	LCOE - New infra[1] (c€/kWh)	11.4
Annual OPEX	5		

Energy TWh/y elec / TWh/y H2

Produced - Space	750 / 0	Prod. Mt H2/y Space	0
Produced - New infra[1]	1'223 / 0	Prod. Mt H2/y New infr	0
Produced - Exist. infra	118 / 0		
		EROI - Space only	612x
		EROI - New infra[1]	29x

Carbon CO2eq (over 30 years)

Intensity - Space	0.7g/kWh	Net avoided[2] - Space	9'637Mt
Intensity - New infra[1]	15g/kWh	Net avoided[2] - New inf	15'183Mt

Table 23 - scenario 5bis KPIs

Scenario 6 – DSR GEO Solar fuel cell: Detailed KPIs

PRELIMINARY

Space and ground settings

Technology	DSR	Mass in orbit	1'289kt
Orbit	GEO 36'000km	# of launches	18'421

Time to launch all satellites fixed to 20 years

# reflectors	82'086	Reflector diameter	1km
Spot diameter	330km	# of ground stations	1

Scalability | Technology maturity | Risks

H2

1 new mega solar fuel cell plants outside Europe

Main outputs

Financials €bn

CAPEX space	327	LCOE - Space only (c€/kWh)	0.2
CAPEX ground	0	LCOE - New infra[1] (c€/kWh)	0.2
Annual OPEX	7.4		

Energy TWh/y elec / TWh/y H2

Produced - Space	0 / 750	Prod. Mt H2/y Space	22'514
Produced - New infra[1]	0 / 18'850	Prod. Mt H2/y New infr	565'569
Produced - Exist. infra	0 / 0		
		EROI - Space only	+3000x
		EROI - New infra[1]	+3000x

Carbon CO2eq (over 30 years)

Intensity - Space	<1g/kWh	Net avoided[2] - Space	15'825Gt
Intensity - New infra[1]	<1g/kWh	Net avoided[2] - New inf	15'986Gt

Table 24 - scenario 6 KPIs