SOLARIS PROGRAM
SPACE BASED SOLAR POWER

DIRECT-SUN-REFLECTION (DSR) PRE STUDY

Presentation to stakeholders

DECEMBER 13TH 2023

Direct Sun Reflecting
Booster of Green Energy

TALDA consortium federates leading energy & space actors around a SBSP system expected to offer the lowest TTM[1], technological risk and competitive cost of energy

TALDA consortium members

ThalesAlenia Space
a Thales / Leonardo company

DASSAULT AVIATION

ARTHUR D LITTLE

Air Liquide

ENGIE Laborelec
RESEARCH & INNOVATION

…leveraging the heritage of our former ADL colleague who initiated the Space Based Solar Power concept

PETER GLASER (ADL 70's)

Our purpose & approach

How to produce **green energy** leveraging the sun energy and the **existing solar infrastructure** with a Space based solar concept that can be deployed in the **shortest time-frame** and at the **most competitive cost?**

Apr	**KO**	- Launch of the pre-study
May	**SKR**	- Stakeholder requirement - Use case selection
July	**ASR**	- Technology requirement & assessment - Architecture trace space - Reference architecture selection
Oct	**AKR**	- Architecture design in space and on the ground - Evaluation of cost, energy and environmental competitiveness
Dec	**FP**	- Final presentation - Communication to stakeholders

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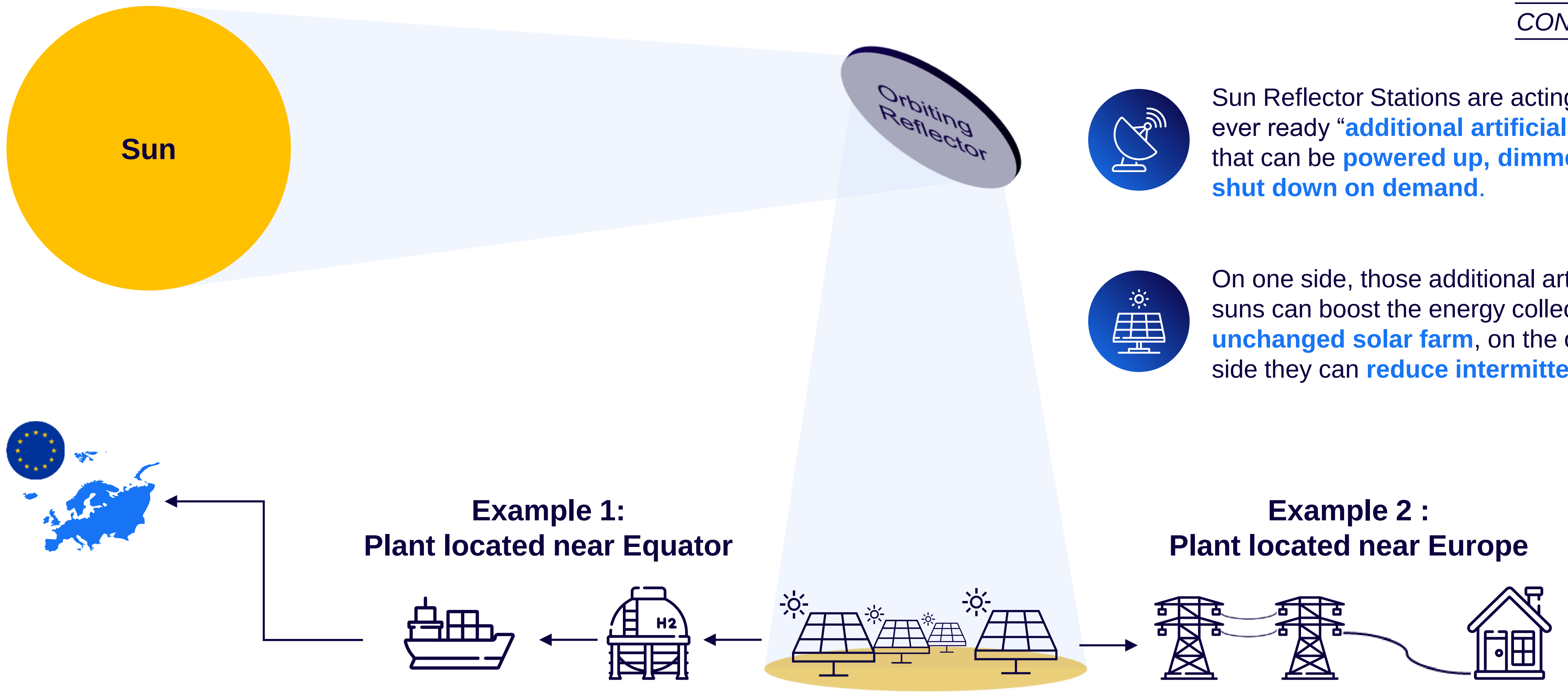
Note: 1) Time to market

Source: Arthur D. Little

The concept is based on increasing sunlight on photovoltaic panels by redirecting the solar light via direct or indirect reflection system on space

CONCEPTUAL



Sun Reflector Stations are acting as ever ready "**additional artificial suns**" that can be **powered up, dimmed or shut down on demand**.

On one side, those additional artificial suns can boost the energy collected by **unchanged solar farm**, on the other side they can **reduce intermittency**

Example 1:
Plant located near Equator

Example 2 :
Plant located near Europe

H^2 / E-fuel

PV panels

Direct connection to grid

Source: Arthur D. Little

Our architecture has several potential use cases identified with stakeholders that will contribute to amortize the total cost of ownership

Energy collection site	**Desertic area near equator**	Isolated country-side	Offshore platform near coasts		
Energy produced	**Hydrogen or other[1]**	Heat & warming	Electricity for a grid	Light	
End user	**H_2 provider**	Local industrial or farmer	E-Fuel provider	Electricity provider	Electric network operator
End user location	**In Europe**	Outside Europe			
Final use	**Industrial & chemical process**	**Green heavy mobility**	Hourly electric use cases	Building	Agriculture
Value proposition	**Green H_2 without additional CAPEX**	**Clean energy without storage**	Accelerate the photosynthesis		

Note: (1) E-ammoniac, e-methanol…, (2) Institutional users such as chemical plants, military bases, isolated towns, large mining and manufacturing operations, electric rail transportation systems

Source: Arthur D. Little

A requirement List has been set up based on stakeholders’ interviews in phase 1

N°	Criticality	Requirement	Electricity	Green molecule
Section 1		Functional requirements		
SBSP-SYS-011	mandatory	The SBSP System shall **direct the light beam or solar power** in space to Ground power station on Earth	yes	yes
SBSP-SYS-012	constraint	The nameplate capacity of each Ground Power Station with the SBSP System shall respect **the grid and connection requirements due to it intermittency**, with a maximum of 1 GW subject to each national electricity network constraints	yes	no
Section 2		Mission requirements		
SBSP-SYS-021	mandatory	The SBSP System shall provide **energy carrier power** for commercial use in Europe or renewable power carriers for Europe	yes	yes
SBSP-SYS-026	mandatory	The SBSP System shall not be designed to be easily used to **harm humans on earth**	yes	yes
Section 4		Environmental requirements		
SBSP-SYS-041	mandatory	The lifetime operations for the solar power satellite(s) in the SBSP system - i.e. the entire orbital lifetime of the system including contracted launch (if offer available), servicing, and disposal activities - shall result in **zero space debris.**	yes	yes
SBSP-SYS-043	mandatory	The system should be **environmentally acceptable in all respects**, including air pollution, water pollution, thermal pollution, hazards, land use, and any other unique factors associated with the particular nature of the system. The system, for example, must meet environmental standards (presently not well-defined) and public exposure to its light beam.	yes	yes
Section 5		Operational requirements		
SBSP-SYS-0510	mandatory	The SBSP System shall be able to **start / stop or redirect the light with a response time <15min** (tbc)	yes	yes
SBSP-SYS-0505	required	During a scheduled download session, the **system availability is available shall be > 99%** (tbc)	yes	yes
Section 9		Physical requirements		
SBSP-SYS-091	mandatory	**The combined capability of all Space Solar Power Plants operating shall generate either up to 750 TWh (TBC) per year of operation by 2050 for electricity or 10% of the European hydrogen consumption forecast in 2050, i.e. ~100Mt/year.**	yes	yes

Source: Engie, Arthur D. Little

The DSR concept is not new and several studies has been developed for lighting or energy supplying, limited until now by technology hurdles or cost competitiveness

1929
Hermann Oberth

Concept of orbiting mirrors to reflect sunlight to earth

- Mathematical demonstration of the concept. However, **technology was not advanced enough to implement it.**

1967
A.G. Buckingham

DSR for illumination purposes

- **Illumination use cases analysis,** including **military applications** (Vietnam war).
- **Existence of technology** to fabricate and launch large solar reflectors, **projects** cancelled due to the anticipated early end of the war.

1970
Krafft A. Ehricke

Use cases for "space light"

- Identification of "space light" use cases: **illumination, improving plant growth, generating electricity,** and **controlling climate.**

1979
Kenneth W. Billman
Krafft .A. Ehricke

SOLARES & SOLETTA constellation design

- **SOLARES program:** 80 000 orbiting solar reflectors to produce 220 GW of electrical power.
- **SOLETTA constellation** at 4200 km, delivering up to 180 GW of power with a 42 km diameter spot on Earth.

1982
NASA

System design of DSR for illumination

- **Synthesis of physical equations** for illumination from space.

1990'
Znamya

First deployment

- Russian space-mirror experiment **illuminates 5km diameter wide spot** from Southern France to western Russia

2020'+
John. C. Mankins
SolSpace, Mirasolar

Solar power momentum

- Several updated studies about **orbiting solar reflectors for power plants** have being presented (73rd International Astronautical Congress, Paris, in September 2022)

Source: Dassault Aviation, Arthur D. Little

To select the reference architecture, 12 combinations of options have been considered and assessed in terms of cost, EnROI, CO2 footprint and risks

3 Space options, all based on reflection designs

1. Direct Sun Reflection in LEO
2. Solar Coherent Light in GEO
3. Direct Sun Reflection in GEO

X

4 Ground options

- A Solar PV
- B Solar PV coupled with electrolysis
- C Solar fuel cell
- D Wavelength-adapted solar PV

Source: Arthur D. Little

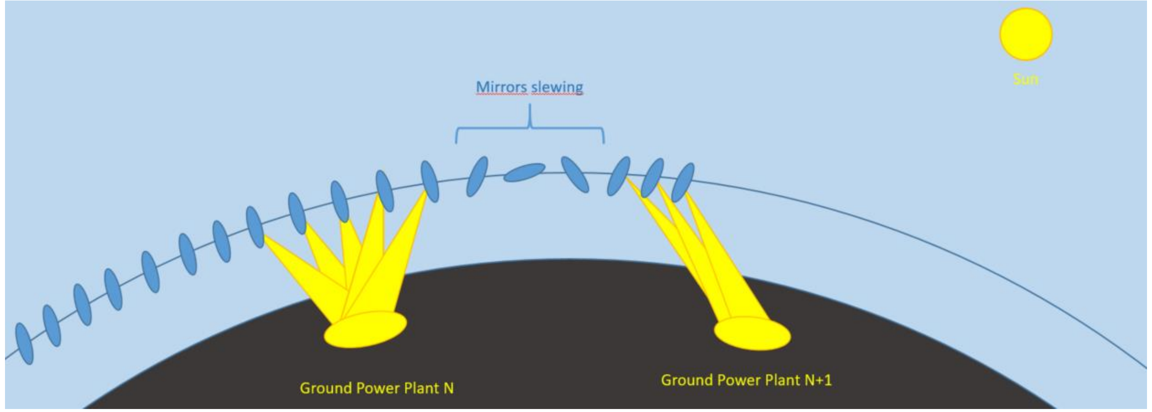
① Direct Sun Reflection (DSR) was considered at 890km-orbit to optimize drag force, spot size on Earth and possibility to illuminate an area twice a day (2/2)

Scenario variables

	Hypothesis
Orbit	**SSO[2] at 890km**
Number of reflectors	**3,987 (parabolic)**
Diameter of reflectors	**1km**
Reflectors in visibility[1]	**252**
Spot on Earth diameter	**8.3km**
Irradiance on Earth	**1,000W/m^2**

System and hypothesis explanations

- For ground stations, **satellites go over twice a day for 2 hours**
- 890km SSO[2] orbit allows for same local solar time and **orbital period multiple of 12 hours**
- Located **above 800km** to avoid drag force
- Higher orbit would imply larger spot size on Earth (proportional)



Note: (1): reflectors in an elevation less <20° above horizon not considered in visibility because atmosphere dissipation of solar radiation is too great, (2): Sun-synchronous orbit: in which a satellite passes over any given point of the surface at the same local mean solar time; Source: TAS, Arthur D. Little

②

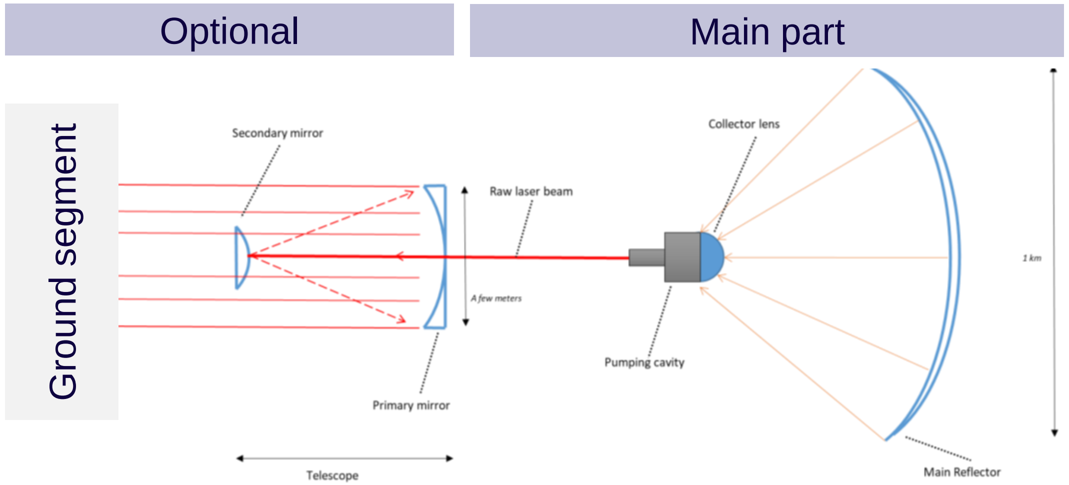
Space Coherent Light (SCL) can be a good architecture to maximize the electricity delivery

Scenario variables

	Hypothesis
Orbit	**GEO[2] at 36,000km**
Number of reflectors[1]	**16,982[1]**
Diameter of reflectors	**750m**
Spot on Earth diameter	**163m**
Irradiance	**1,000 to 2,400W/m^2 @1064nm**

System and hypothesis explanations

- SCL units generate a light beam directly from concentrated Sun light
- Very narrow divergence angle: SCL units high in GEO have a **permanent (24/7) view on the ground power plant (wavelength non in the visible spectrum)**
- After the coherent light generation, a **telescope** is placed to diffuse power: allows for **lower irradiance although enlarging the spot size to fit with the ground size**

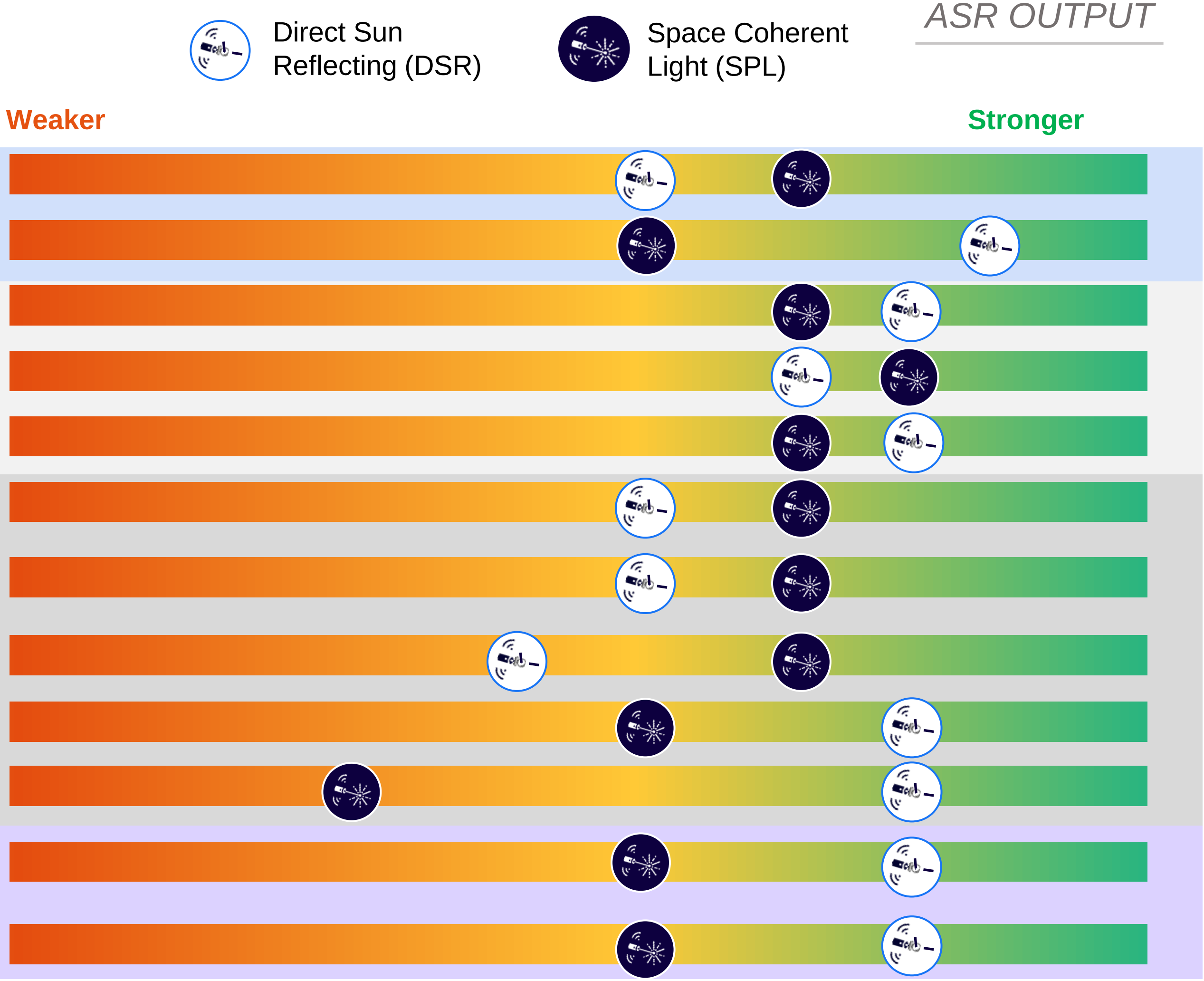


Note: (1): for a conversion efficiency of 10% (2): Satellites in geostationary orbit (GEO) circle Earth above the equator from west to east following Earth's rotation. It means they stay above the same spot on earth constantly
Source: TAS, Arthur D. Little

As a nutshell, the two possible architectures are closed in terms of performance, with eventually a little benefit for DSR especially on security issue

ASR OUTPUT

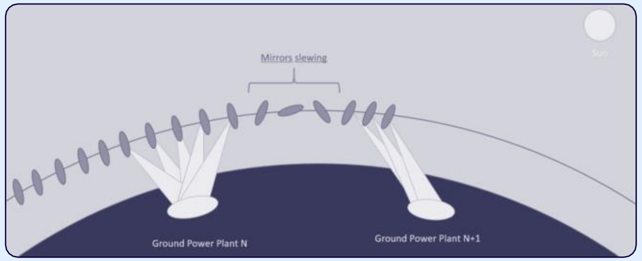
	Key analysis criteria
Addressable market	**Potential delivery of electricity in Europe**
	% of H2 production to meet the 750TWh requirement
Quantitative KPI	**LCOE – Net Infrastructure**
	EROI – Net Infrastructure
	CO2 – Net Infrastructure
Infrastructure deployment	**Space infrastructure complexity**
	Size and weight of space infrastructure for generating 2GW on Earth
	Potential number of used on grid stations in Europe
	Use of existing ground infrastructure
	Security issue on ground zone
Time to deploy	**Availability of needed technology (maturity level ~TRL)**
	Time to market & modularity for deployment



Source: Arthur D. Little

The reference DSR architecture is a train of large reflectors in LEO orbit illuminating a group of existing or new PV plants

KEY PRINCIPLES OF THE DSR TRAIN



- Illuminate simultaneously a single GPS for providing **~1,000W/m^2 …**
- … **during 2 hours…**
- **…** in **dawn & dusk**

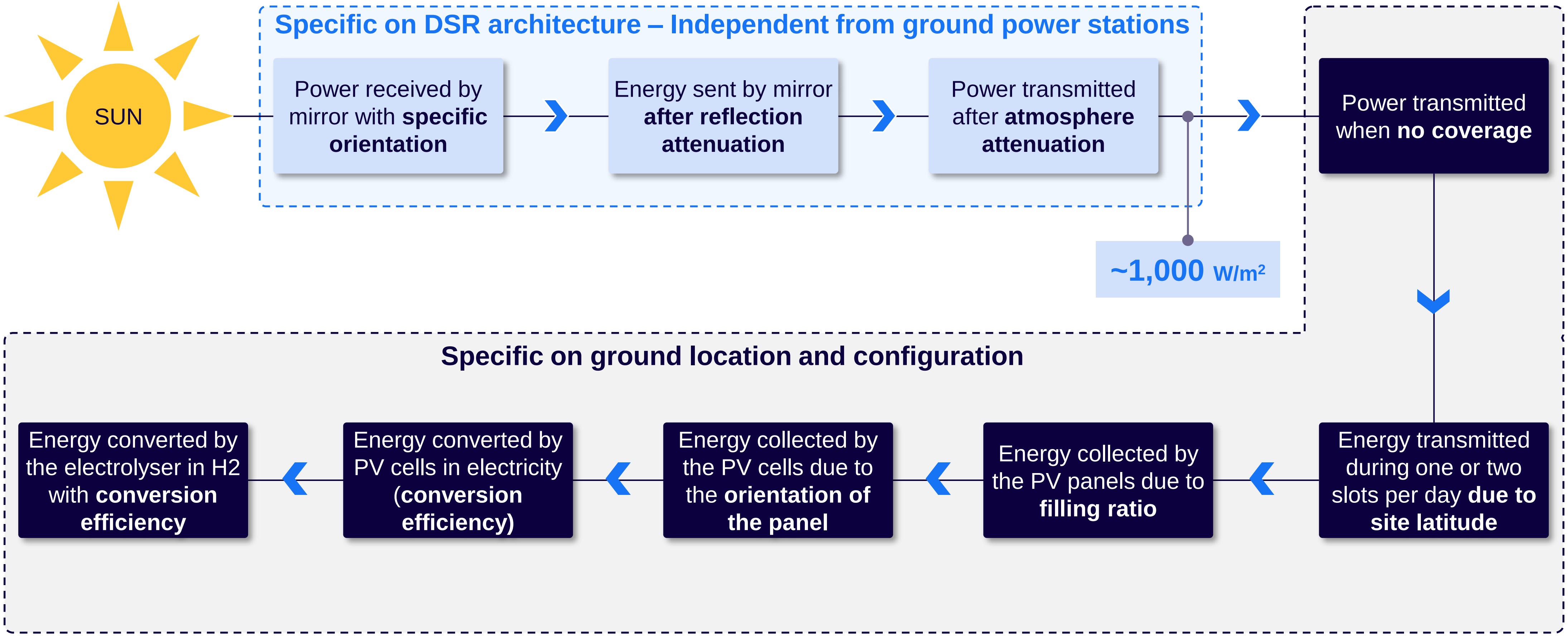
Main difference with RF architecture

DSR is a “Many-to-Many” concept vs. RF is a “One-to-One” concept

Note: 1 W/m2 = ~100 lux

Source: Thales Alenia Space, Narva, Arthur D. Little

Global space to ground model includes factors based on the DSR configuration but most of the attenuation is correlated with ground segment location and configuration



Source: Arthur D. Little

The main ConOps include five main use cases, each focusing on simplicity

	Launch & Deployment	**Assembly**	**Attitude control & maintenance**	**Collision risk management**	**End of life**
OBJECTIVE	**Select the optimal launching strategy**	**Define the assembly process** and **cadence** to optimize launching	**Supply spare parts** in case of maintenance (mirror default…)	**Evaluate the risk** of debris collision and **define corrective actions** to mitigate them	**Avoid any new debris** in space by combining all possible strategies
SELECTED STRATEGY	**LEO orbit & Solar Foil:** Launch to parking orbit (680km) and transfer to final orbit with SF (890km)	**Use an assembly platform** for each SRS before their unfolding and solar sailing to orbit	**Solar foil** for orbit control **Mirror replacement** and / patches for very small debris impact	Perform an **attitude correction** or **orbital correction maneuver** to minimize collision risk & potential damages	**Recycling in orbit** and **generate significant revenues in reselling materials**

Source: Thales Alenia Space, Arthur D. Little

DSR[1] offers to boost the production of green energy of any sun-based ground operator with the best balance low risks/high resilience/high value concept

Leveraging existing ground sun-based technologies: infrastructures, ecosystems, scale effect, future improvement potential

High impact of energy production (+40-60% vs. current state) for any sun-based ground operator without additional CAPEX

Positive business case in terms of costs, energy and CO2 footprint, with potential upside with recycling and reselling materials (evergreen infrastructure)

Modularity and replicability in space leading to full flexibility and resilience for deployment and scale up

5

Additional benefit from DSR

Maturation of key technologies that would be used for other space and/or earth applications

Note: 1) Direct Sun Reflecting
Source: Arthur D. Little

1 DSR can illuminate several ground configurations and technologies that all are compatible with our concept

SEGMENTATION OF POSSIBLE GROUND INFRASTRUCTURE

Type of output	Emerging	Growing	Mature
Light	Cities 		Farm 
H2 or eq.	**Solar Fuel /** Turquoise H2 	**PV & PEM Electrolyzer** 	
Elec	Floating PV[1] 	Solar Thermal[1] 	**PV** 

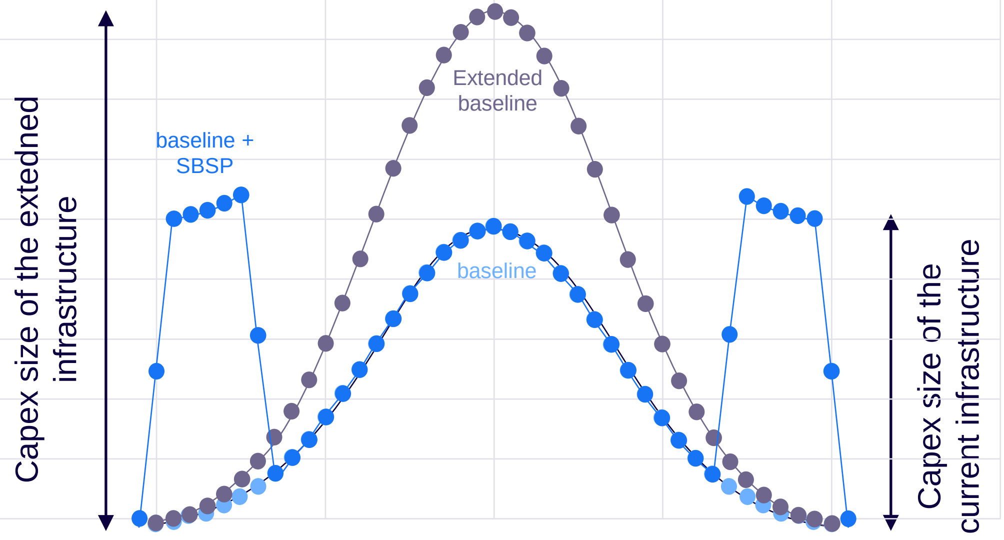
Level of maturity (TRL)

Note: 1) Infrastructure that can be combined with electrolyzer to produce H2 off grid
Source: Arthur D. Little

1 Solar farm operators use case: Boosting energy produced without additional CAPEX

OFF GRID PV & H2 OPERATORS

Surface areas below grey and blue curves are equivalent



BENEFITS

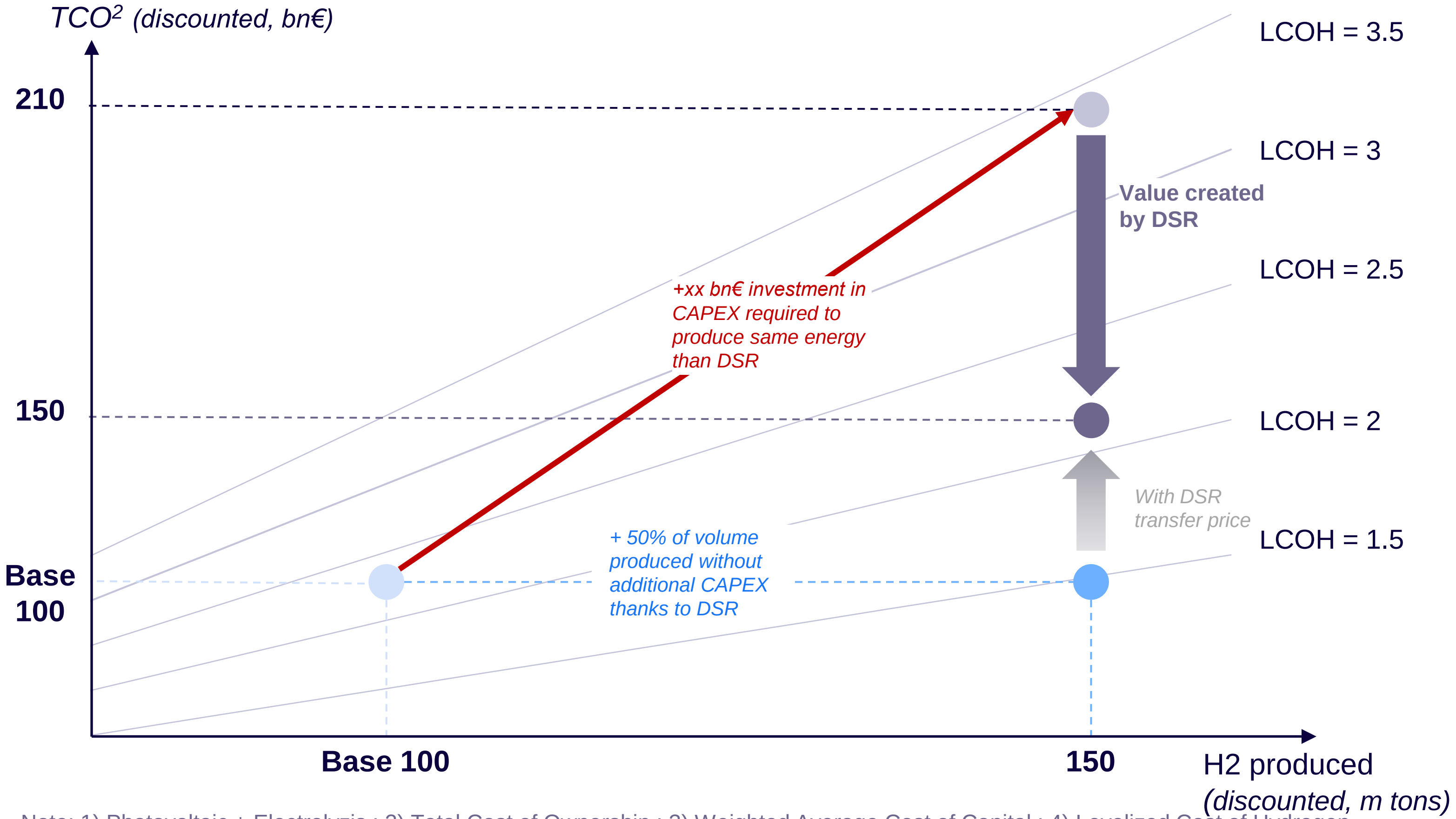
- Increase the H2 output with **no additional CAPEX**
- **Increase ROCE** to generate more revenue

Source: Air Liquide, Arthur D. Little

2 DSR provides a high impact of energy production for any sun-based ground operator

EXAMPLE

LCOH analysis for one single PV + ELY[1] station (not considering ramp-up)



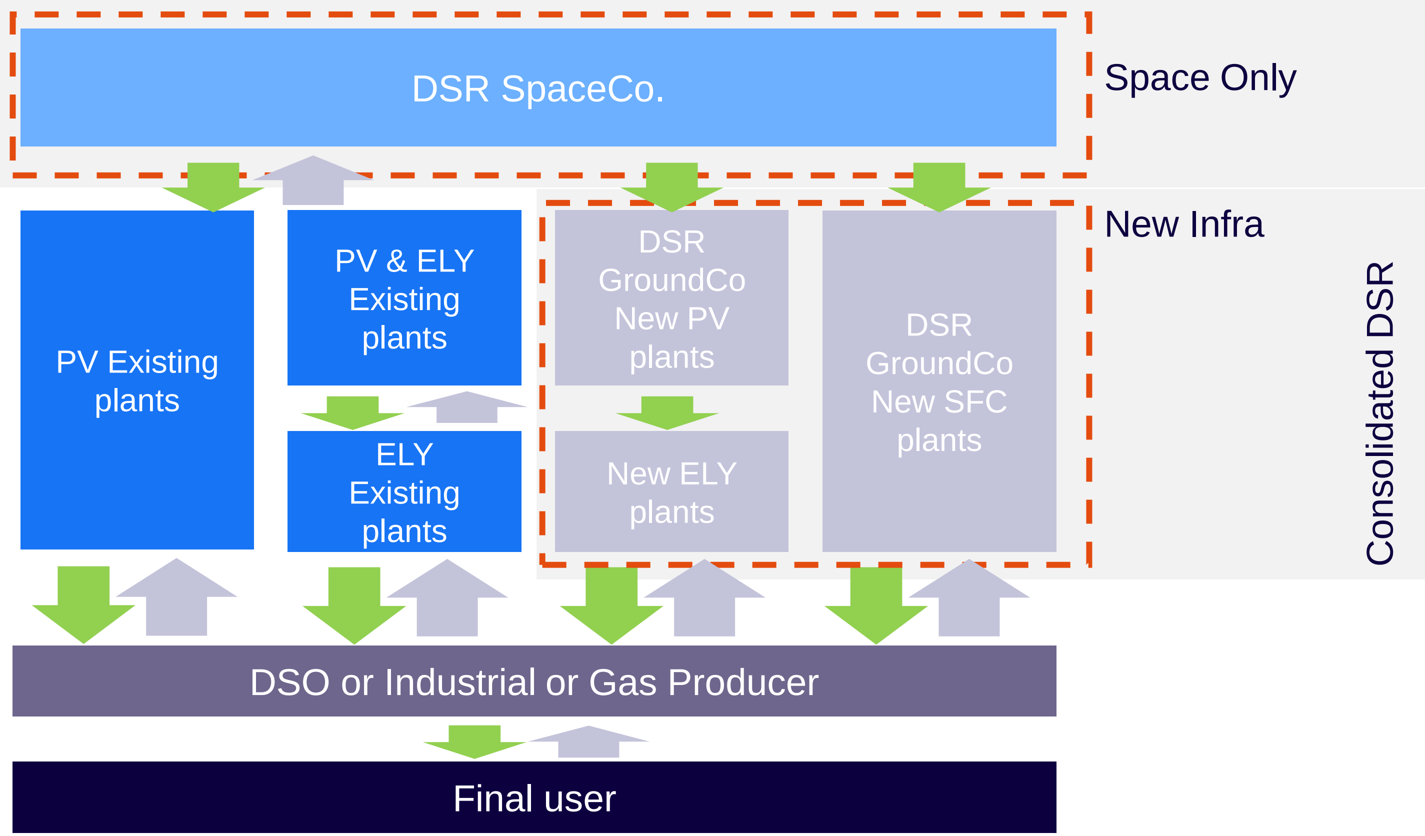
Legend

- ● LCOH[4] from natural illumination only
- ● LCOH incl. DSR without transfer price
- ● LCOH with increased CAPEX to reach same level of H2 production than DSR
- ● LCOH incl. DSR with transfer price

Note: 1) Photovoltaic + Electrolyzis ; 2) Total Cost of Ownership ; 3) Weighted Average Cost of Capital ; 4) Levelized Cost of Hydrogen
Analysis made for one single station deployed from 2036 to 2065 ; Different units are used between the two axis,
Source: Engie, Arthur D. Little

3 In terms of business model, we have designed the Space segment as it will be managed “separately” from the ground segment

DSR Value chain



Source: Arthur D. Little

3 The “Space only” scenario appears to be interesting financially

Key indicators for reference scenario – Space only (2025-2081)

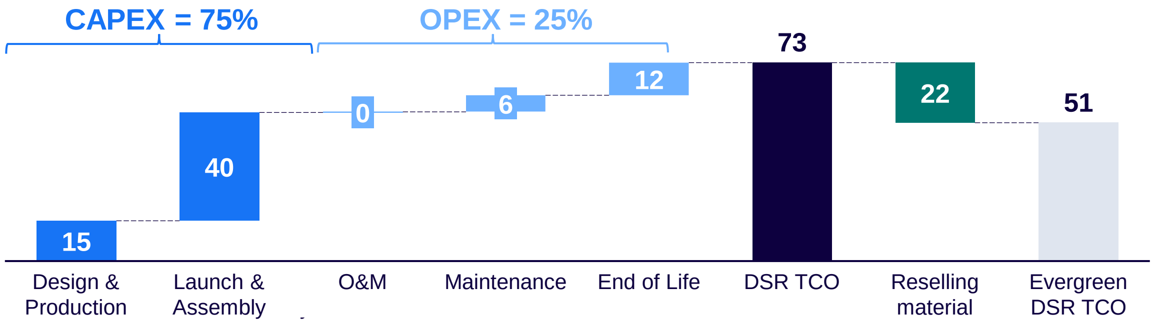
Note: Data for 22 new GPS (10 PV + ELY and 22 SFC) and 8 existing GPS (2 PV and 6 PV + ELY)
1) Net Present Value
Source: Arthur D. Little

3 The “Space only” scenario appears to be interesting financially

Key indicators for reference scenario – Space only (2025-2081)

Lifetime total cost of ownership (TCO)

bn€, 2025-2081, non discounted



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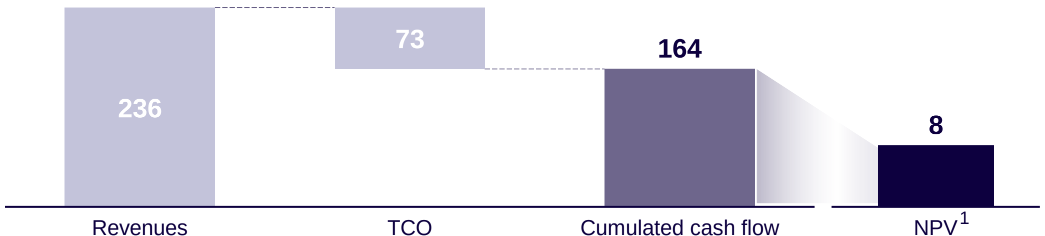

Lifetime total cost of ownership (TCO)

€50-70B
non discounted

Note: Data for 22 new GPS (10 PV + ELY and 22 SFC) and 8 existing GPS (2 PV and 6 PV + ELY)
1) Net Present Value, Cumulated CF discounted at a 10% WACC
Source: Arthur D. Little

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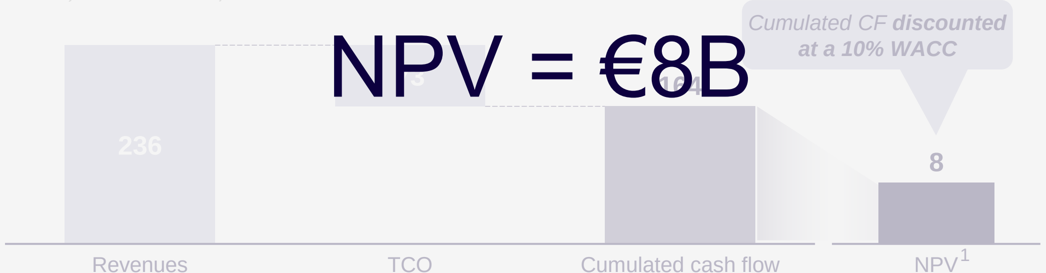
Lifetime financial performance

bn€, 2025-2081, non discounted



NPV = €8B

Cumulated CF ***discounted at a 10% WACC***

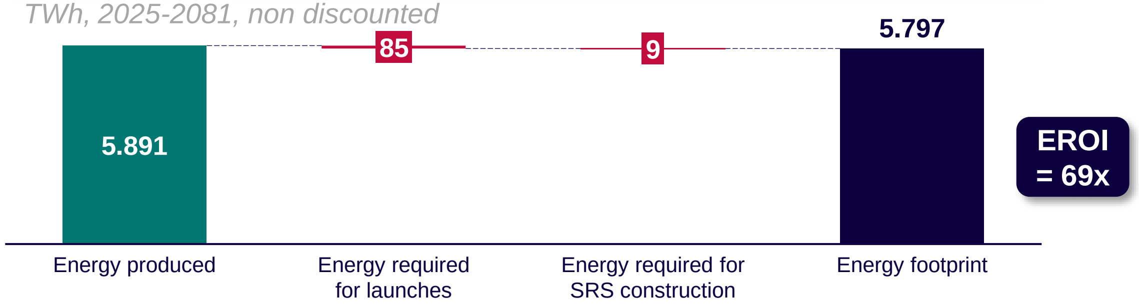
Lifetime total cost of ownership (TCO)

bn€, 2025-2081, non discounted

€50-70B non discounted

Lifetime energy footprint

TWh, 2025-2081, non discounted



EROI = 69x

Note: Data for 22 new GPS (10 PV + ELY and 22 SFC) and 8 existing GPS (2 PV and 6 PV + ELY)
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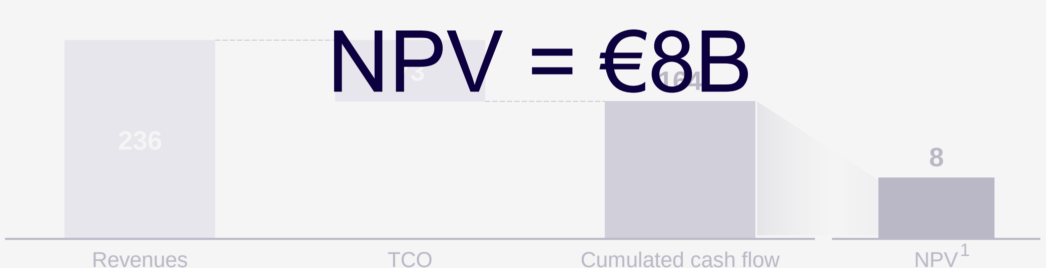

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bn€, 2025-2081, non discounted

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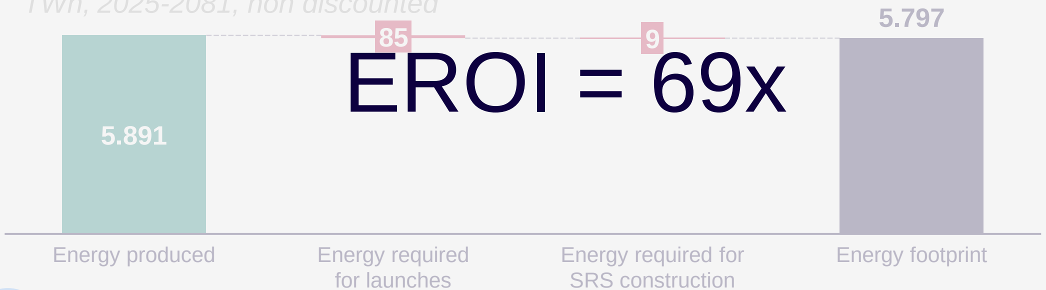
Lifetime energy footprint

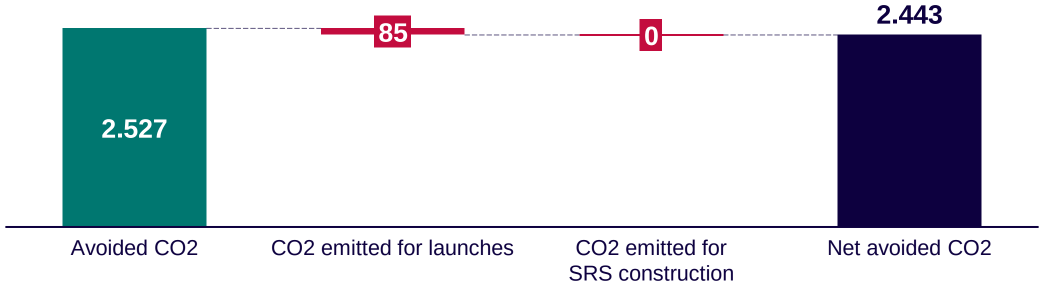
TWh, 2025-2081, non discounted



EROI = 69x

Lifetime net carbon avoided

mtons CO_2, 2025-2081, non discounted

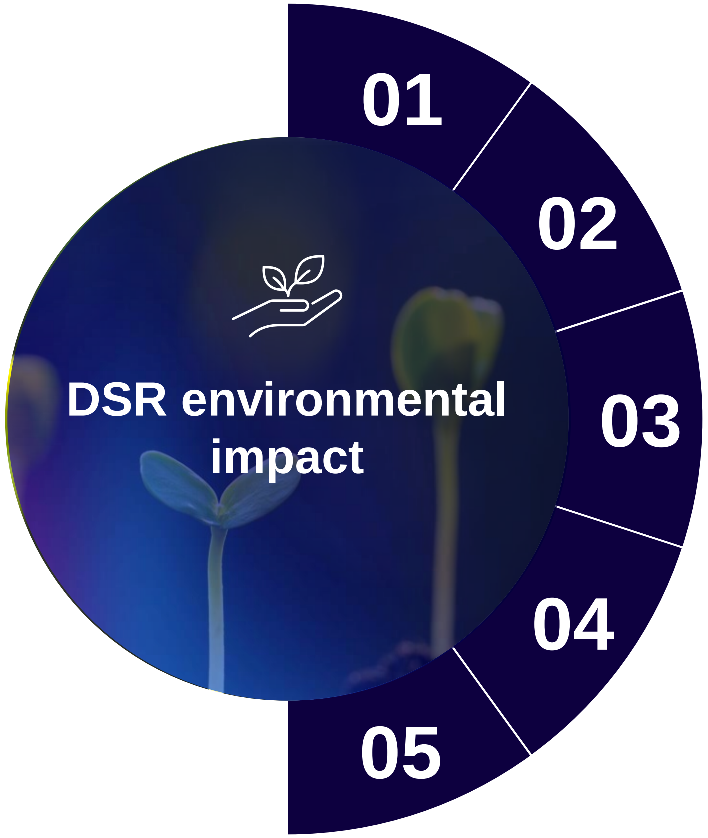


Note: Data for 22 new GPS (10 PV + ELY and 22 SFC) and 8 existing GPS (2 PV and 6 PV + ELY)

1) Net Present Value, Cumulated CF discounted at a 10% WACC

Source: Arthur D. Little

3 Our DSR concept has mitigated issues on environmental impact by nature and a limited light pollution



Human Health	- The intensity will not exceed the sun one - Limit the exposure to dawn & dusk	◔
Flora and fauna	- Limit the spot size and its intensity - Select the appropriate location	◔
Interference on Infrastructure	- The intensity will not exceed the sun one - Natural light	○
Launch / Deployment	- Limit the weight of space segment - Use LH2 rather than LCH4	◔
Ionosphere & Atmosphere	- The intensity will not exceed the sun one - Natural light	○

● Strong potential impact ○ No potential impact

Source: Arthur D. Little

3 Most of the potential risks are mitigated with DSR concept, except the debris in LEO that could need to associate DSR with SCL

RISK ANALYSIS

10 RISK ANALYSIS

3 Most of the potential risks are mitigated with DSR concept, except the debris in LEO that could need to associate DSR with SCL

Source: Study on cost-benefit analysi

IDENTIFIED KEY RISK FACTORS

1. Low interest and support from key governmental stakeholders and policy makers
2. Slower than expected development rate for the key technologies
3. Demonstrator fails to prove viability of the concept/achieves lower efficiency
4. Potential disagreement in terms of frequency (dispute with the ITU)
5. Strong public opposition
6. Launcher performance does not achieve necessary scale and cost
7. Failures during in-orbit assembly
8. Limited availability of required raw materials
9. Bankruptcy of industrial partners
10. Disruption in operation due to technical issues
11. Reduction in electricity prices

10 RISK ANALYSIS

Main risks in the construction and deployment phase include issues with reusable launch systems/in-orbit assembly as well as limited availability of raw materials

ID	Risk type	Risk category	Description	Root causes	Probability	Impact		DSR mitigation actions and resulting proba x impact	
06	Construction & deployment	Technology/ Economic/ Environmental	**Launcher performance does not achieve necessary scale** and cost by the time of construction & deployment	Slower than expected development of fully reusable launch system		**Increased cost of deployment** can lead to less competitive LCOE as more launches are needed to deploy the satellite		Starship could use as a launcher Modular architecture that support delays	
07	Construction & deployment	Technology/ Economic	**Failures during in-orbit assembly**	Disruption in communication with assembly units/robots Collision with space debris		**Increase construction time** and overall deployment cost		Direct to Orbit deployment is sub-optimal but possible	
08	Construction & deployment	Economic	**Limited availability of** required **raw materials**	Disruption in global supply chains		**Increased construction cost** and delayed deployment **Increased dependency**		Modular architecture with iterative designs than can support several materials (ex Kapton vs Keep)	
10	Construction & deployment	Technology	**Disruption in operation due to technical issues**	Space infrastructure no more controllable		**Loss of control** **No energy provided**		SRS will burn in atmosphere withour danger No safety risks	
12	Construction & deployment Exploitation	Political	**Change in the commitment of public and private partners**	No more deployment in space No more fund		**Lack of SRS to produce the outputs requested**		Modular architecture, with impact possible with quite few mirrors	

◕ High ◔ Low

Source: Arthur D. Little

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IDENTIFIED KEY RISK FACTORS TO MONITOR FOR THE NEXT STEPS

Reduction in electricity prices
→ WORLD WIDE SCOPE & MODULAR ARCHITECTURE

Launcher performance does not achieve necessary scale and cost
→ PROTEIN

Demonstrator fails to prove viability of the concept/achieves lower efficiency
→ DEMO

High impact of debris in LEO on cost and complexity of operations
→ DEMO ON DSR & SCL

Source: Study on cost-benefit analysis of space-based power generation for terrestrial energy needs – ESA, Arthur D. Little

4 Many of the large infrastructures are migrating from Large Single Unit pattern to Multiple Units “Constellation” to better mitigate risks, like the DSR design

Large Single and complex Unit

Multiple modular and evolutive Units

- Thanks to its **design (Many-to-Many vs One-to-One)** and the **Protein** project, DSR could start its **commercialization in 2033** and be at **full scale in 2043**

Source : HBR “Make Mega projects more modular” – Dec 2021 – Ben Flyvjberg, Arthur D. Little

The global roadmap until full scale deployment is based on six main workstreams

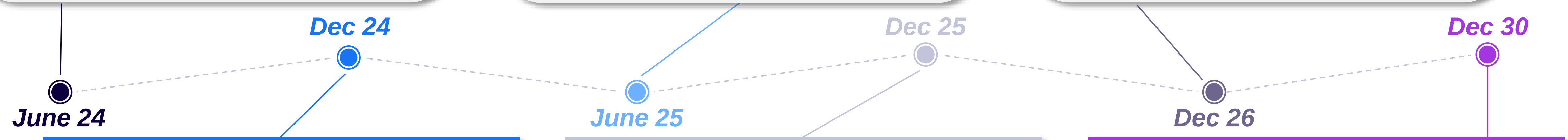
Demonstrator	TDA	Facilities building	Full scale DSR deployment	Stakeholders' alignment & infra building	PROTEIN interface
Develop a sub-scale demonstrator to **validate the key components** of the space and ground segments	**Mature the key technologies** mainly on space	**Build the main facilities** to industrialize the production of the SRS[1]	**Produce, launch, deploy and operate** the SRS[1] in space	Involve the ground operators and other stakeholders to **convince on the DSR value** **Build the additional GPS** to ensure the right output sizing	**Coordinate with the PROTEIN project** to ensure the feasibility to load 3 SRS[1] in a single launcher for LEO 98° at the best costs and minimum CO_2 footprint

Note: 1) Sun Reflector Station

Source: Arthur D. Little

Our recommended approach is to keep the momentum of the project with key milestones until MVP end of 2030 at the latest

PRELIMINARY



1. Phase 0/A/B1 study

- Further analysis of SBSP concept
- Sub-scale space-based demonstrator proposition
- ***PV studies***

→ Milestone ADD[1]

2. ConOps & mission analysis

- ***Grid connection and risk analysis***
- ***Communication module development***
- ***Technical & industrial ecosystem operational***

→ Milestone SSDD[2]

3. Ground demonstration

- System simulation modelling (mission analysis, AOCS, formation flying, mechanical, thermal)
- Structural mechanical testing
- Zero-G demo with ground support equipment for structure deployment
- If needed, Zero-G parabolic flights
- ***Environmental impact studies***

→ Milestone GDV[3]

4. Subscale space demonstrator

- 100 – 1000 m mechanically representative sub-scale reflector platform
- Autonomous deployment in space
- Orbit raising Solar sailing
- CMGs attitude control
- Membrane impacts collision detection & analysis
- ***Pilot GPS identified and adapted***

→ Milestone SRFV[4]

5. Flight of multiple reflectors

- Connection with GPS
- Validate the dynamic behavior of group of reflectors

→ Milestone MRFV[5]

6. Technical demonstrator

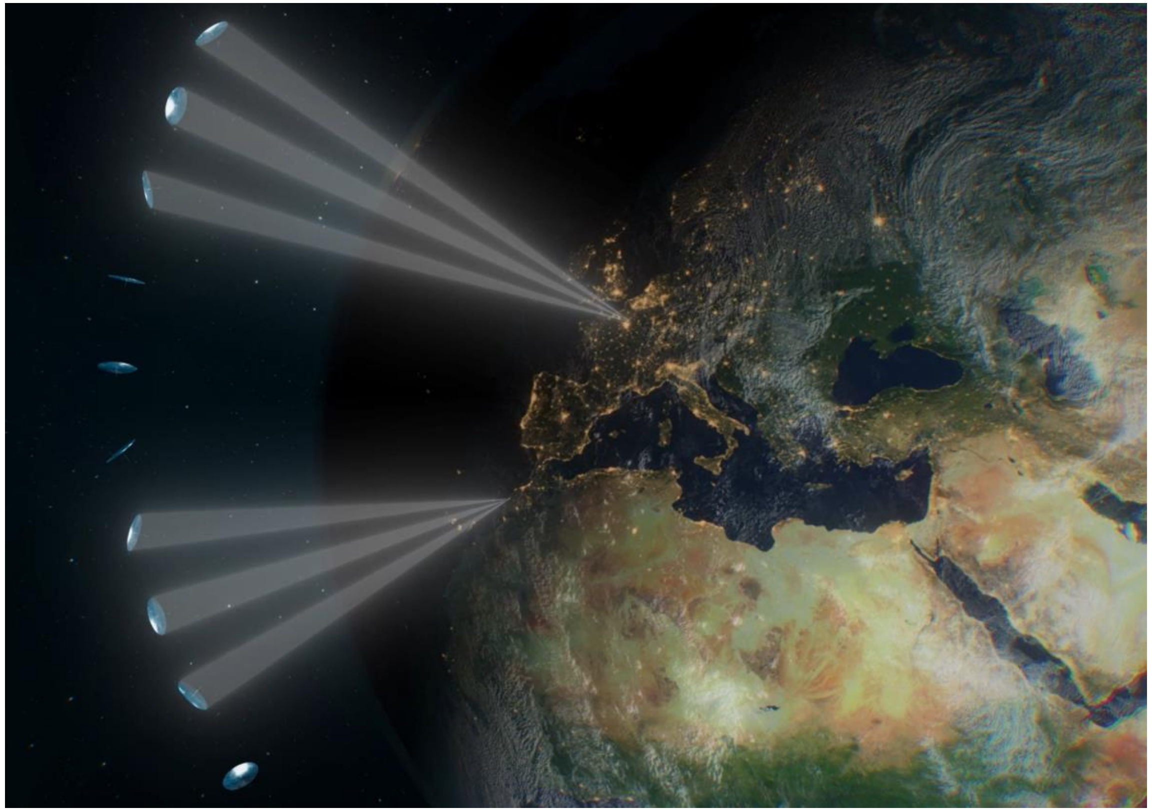
- Initiate the business with a subscale reflector (potentially the same as the previous) to illuminate $10W/m^2$ during 10' and CL demonstrator
- ***SFC technology maturation delivered***

→ Milestone MVPO[6]

Note: 1) Architecture demonstrator definition ; 2) Subscale demonstrator definition ; 3) Ground demonstrator validation ; 4) Single reflector fly validation ; 5) Multiple reflector fly validation ; 6) Minimum viable product operational

Source: Thales Alenia Space, Engie, Arthur D. Little

Space can provide a lot of value for energy market on earth



Reflecting systems on space offer a major opportunities for solar infrastructures operators to boost their performance

This project -thanks to ESA- allowed to initiate a strong collaboration between space and energy leaders

Within few months, our collaboration has demonstrated that breakthrough innovation like DSR & SCL were feasible and attractive

Let’s continue to work on this amazing challenge to get a more sustainable world of energy thanks to space

ARTHUR D LITTLE

THE DIFFERENCE

with collaboration of space and energy leaders

ThalesAlenia Space
a Thales / Leonardo company

ENGIE Laborelec
RESEARCH & INNOVATION

DASSAULT AVIATION

Air Liquide

for the Solaris program of

esa