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

ESA – TALDA - TN1 : STAKEHOLDER EXPECTATION REPORT

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ESA – TALDA - TN1 : Stakeholder expectation report

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In the framework of
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Written by
Aurélie DURAND MORIN

+ 33 7 49 96 82 55
aurelie.durandmorin@engie.com

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Verifier
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Approver
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Applicability
This report proposes a summary of all the expectations and requirements issued from interviews done with energy value chain stakeholders.

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1. Introduction

Leading space and energy actors are working together around a **Space Based Solar Power** system expected to offer the lowest time to market, technological risk and infrastructure investment.

The TALDA consortium composed by Thales Aliena Space, Air Liquide, Laborelec, Dassault and Arthur D. Little are selected to propose a Preliminary Feasibility Study of the Direct Sun Reflector (DSR) concept.

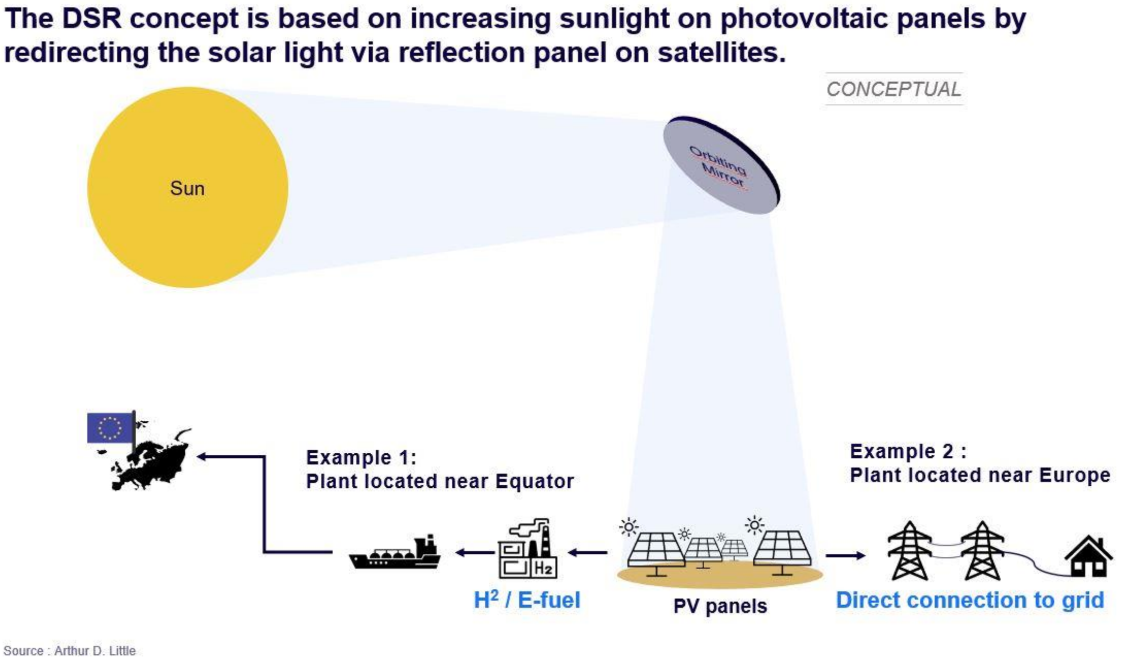


Figure 1 : The DSR concept

The DSR concept is based on increasing and/or extending sunlight on terrestrial photovoltaic panels by redirecting the sun light via reflective panels on satellites. From the terrestrial solar farms point of view, such Satellite Power Stations (hereafter designed as SPS) are acting as ever ready “additional artificial suns” that can be powered up, dimmed or shutdown on demand. On the one side, those additional artificial suns can increase energy collected by a typical solar farm, on the other side they can counter-act intermittency.

This additional resource allows benefiting of favorable conditions outside of Europe as far as the solar power is transformed and stored in renewable energy carriers (not only electricity) and then delivered in Europe, as least partially.

Indeed, 80% of European energy consumption comes from fossil energy carriers (coal, oil and gas) imported from hydrocarbon rich countries. In particular, most fit production sites are located in uninhabited areas which allow the use of direct sunlight reflection from equatorial orbits after conversion.

An analysis of the two main SBSP transmission concepts, Radio Frequency (RF) and Direct Sun Reflection (DSR), shows that DSR concept has significant advantages -even if it does not perfectly address the use cases with direct connection to European electric grid- that should be further investigated:

- Lower technological complexity / risk: readily availability of many critical needed technologies to accelerate the development pace;

- Large addressable market to replace fossil energy (with green hydrogen or e-Sustainable Aviation Fuels “e-SAF” for instance) and eventually green electricity if a grid connection is available;

- Lower investment required as the DSR concept can leverage existing ground solar farms with PV, at the cost of constraints on the location where the energy is delivered;

- Shorter time to market, as ground investment can be reduced and space segment is simple and launchable eventually with existing launchers

Therefore, the DSR concept should be seen as a complementary solution to RF-based concept, allowing a quicker deployment for addressing the non-electrical energy consumption.

In this context, a Space Based Solar Power infrastructure based on the DSR concept can highly contribute to reach the NZE (Net-Zero-Emission) scenario defined by the IEA, notably if it targets the non-electric energy market (thermal solar plant, solar molecule… that are fully compliant with the DSR concept and allow to produce decarbonized non-electrified energy). . Our concept, as proposed and described afterwards by the Consortium, potentially offers an infinite and decarbonized energy at a competitive cost and contribute to the main measures identified:

- It can help to cut the fossil fuel emissions by producing decarbonized hydrogen, directly or through carbon capture processes, for direct or indirect applications in industry, transport and buildings,

- It can help to increase the volume of clean electricity with a higher efficiency,

- It can contribute to increase the efficiency of existing solar farms,

- It can represent a big boost to clean energy innovation.

It can therefore be a key enabler for Net Zero Emission scenario, supposing a technical feasibility and a cost competitiveness. The objective of this Pre-Phase system study and more specially this deliverable, is to identify and define the stakeholders expectations and requirements for a future Space Based Solar Power System which can serve European energy needs.

This report summarizes all the interviews done in April 2023 to collect feedbacks from energy stakeholders concerning the opportunity to deploy a SBSP. All the energy applications and energy market evolution are explained in order to defined the requirements and constraints to respect and applied on the space mirror. All these outputs result in the first Work Package WP100 of the pre-study.

The objectives are to:

- Identify their main expectations on the DSR Concept

- Identify the main benefits and constraints of DSR
- Prequalify the most promising commercial use cases.

The methodology of the approach, the perspective on the energy value chain and the fit analysis of output vs. DSR will be presented in this deliverable.

2. Methodology of the approach

2.1. Methodology and tools

To collect feedbacks from the energy stakeholders, the TALDA consortium uses a guide. This guide follows a clear and objective methodology and helps structure the capturing of info from the interviews. (See **Error! Reference source not found.**)

Starting from the different energy vector (outputs) which are able to be produced with the sunlight of the DSR concept, we collect the point-of-view of different energy value chain stakeholders about their future needs, their urgency, which criteria are important and which KPI's could be defined and followed.

These stakeholders' expectations enable to define potential operational. This study will enhance to the two most promising use cases where the specific requirements will be identified. These requirements will be key data to define the space solution which could be developed in space.

The TALDA consortium methodology is based on interviews. Some of them are realized with different stakeholders selected by ESA, and others are done inside ENGIE group which enables to have a diversification of point of view (renewables, hydrogen, heat solution, lightening….). The interviews last between 1 hour and 1h30.

A survey (see **Error! Reference source not found.**) is already done to collect feedback from stakeholders (inside ENGIE and external companies) interested in the DSR concept which were not available during the interview's sessions.

2.2. Interviews and questionary

This report includes all the interviews of stakeholders selected by ESA between April the 17th and 25th . It also includes the interviews and answers issued from the survey done with selected stakeholders from ENGIE.

- Stakeholders selected by ESA

Stakeholder Name	Organization	Role
Axel Becker	EDF	Head of New Technologies in Solar
Ginevra Guzzi	Microsoft	Sr. Program Manager, EMEA Energy
Richard Hall	Independent	Energy Sector Expert
Jan HOOGSTRAATEN	BritNed	Manager Regulatory Affairs
Shima MOUSAVIGARGARI	TenneT	
Alkis Romeos	SHELL	Commercial Partner Manager / Gamechanger
Liam Ryan	EirGrid Group / ENTSO-E	Chief Innovation and Planning Officer / Chair
Lars Schellhas	Schellhas Engineering	Energy Expert, Consultant
Hans van Tol	DutchPowerGroup	Chief Executive Officer
Pavel Zolotarev	TransnetBW	Head of Energy and Balancing Markets

Table 1 : Stakeholders selected by ESA

- Stakeholders selected by ENGIE and ADL

Stakeholder Name	Organization	Role
Jan MERTENS	ENGIE R&I	Sciences Chief officer
Pierre CRESPI	Air Liquide	Chief Innovation
Amaury KLOSSA	Arthur D. Little	Partner expert energy market

Table 2 : Stakeholders selected by ENGIE and ADL

- Participants to the survey

Stakeholder Name	Organization	Role
BCO	Engie R&I	senior research program manager. Energy solutions for B2B and B2T.
RVE	Engie R&	Renewable Energy - Research Program Management
AMA	Laborelec	Solar expert
SSA	Engie R&I	Green Gases, decarbonization expert
CCA	Laborelec	Solar expert
HLE	ENGIE	Renewable Energy / Hydrogen - Sectorial strategy analyst
GSA	Independant	Advisor Business Development, Master Industrial Economics (with physics background)

Table 3 : Participants to the survey

All the interviews and the answers issued from the survey are included in the **Error! Reference source not found.**.

The panel of the companies interviewed cover the whole energy value chain :

- With external energy experts, energy provider, energy Transmission System Operator, Distribution network Operators and end users.
- With different outputs like electricity, fuels, H2
- Coming from different countries of Europe

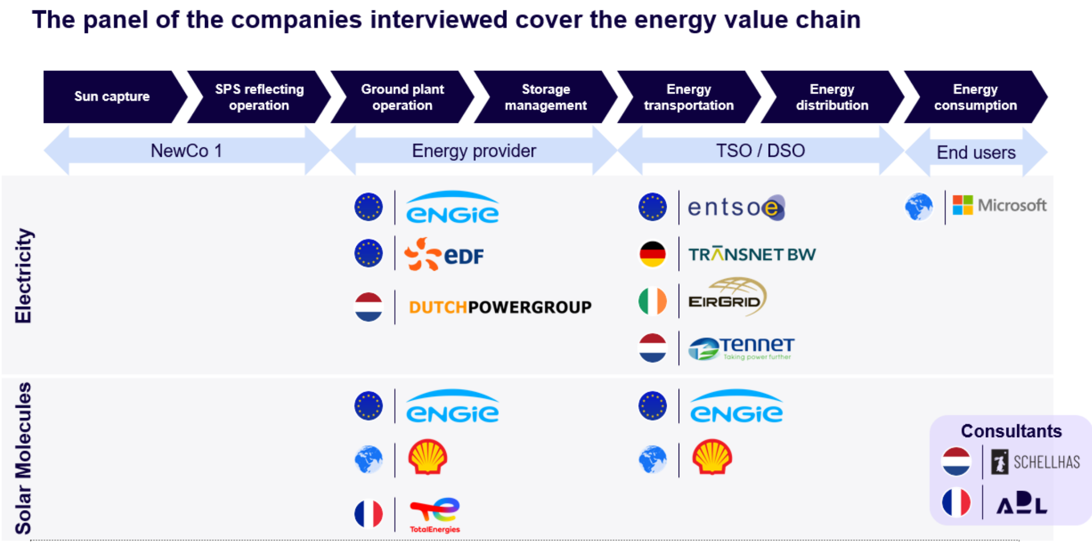


Figure 2 : panel of companies covering the energy value chain

2.3. Global perception about the DSR Concept

The stakeholders consider the concept with a good potential and are relatively confident on its value chain, even if some key issues need to be fixed

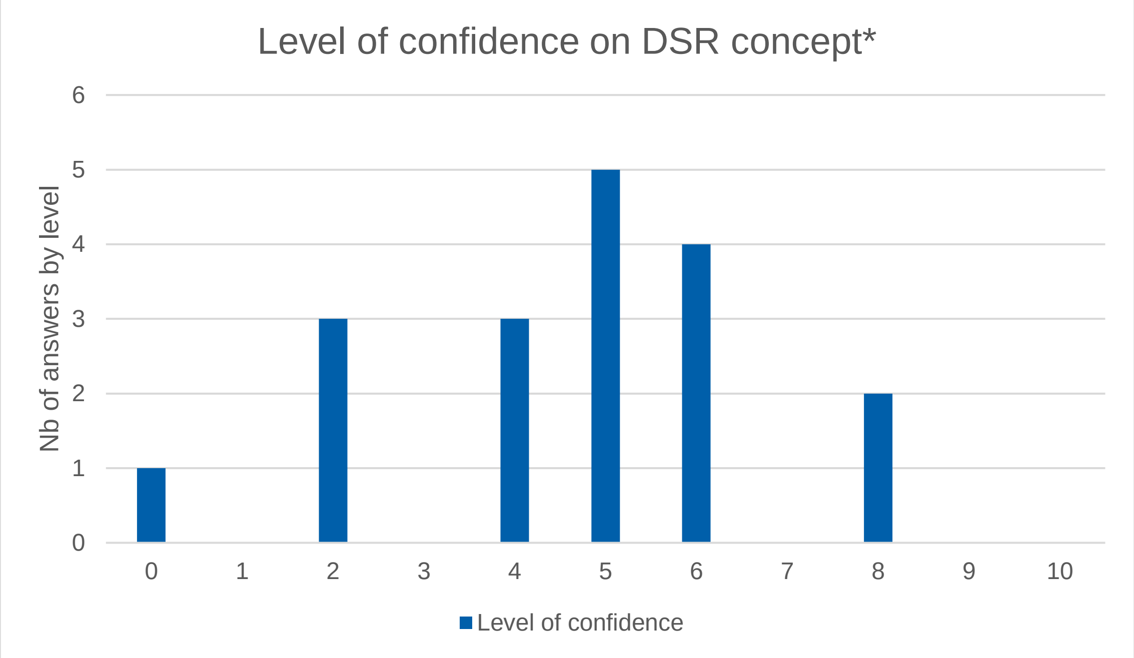


Figure 3 : Level of confidence of the stakeholders

(*) Answer to the question "From 0 to 10, what is your level of confidence on the DSR concept?"

All the interviews were constructive with a positive mindset, although the quantification of the requirements has been quite challenging.

The stakeholder panel covers all the topics regarding each possible solution. A short description with some requirements are proposed hereafter. Some requirements are eligible only for specific outputs.

2.4. Segmentation of the use cases

The table below is the global framework to list all the potential applications, based on 2 main dimensions : the outputs generated by the energy collected by the ground segment, and the location of the ground segment, that is impacted by the illumination period and the spot size constraints.

Output	Europe On Shore	Europe Off Shore	Outside Europe
Green Electricity	**YES**	YES	NO
Green molecules	NO	POSSIBLY	**YES**
Green desanalised water	NO	POSSIBLY	**YES**

Green Heat	**YES**	NO	**YES**
Green warming	**YES**	NO	**NO**
AgriPV	**YES**	NO	POSSIBLY
Enhanced Crop	NO	NO	**YES**
Permanent lighting for human	**YES**	NO	**YES**

Table 4 : The potential applications in Europe and outside Europe

Globally three key issues are shared among the stakeholders:

- the financial aspect with the aim of achieving the lowest Levelized Cost Of Energy production (LCOE). Green energy could justify a price premium compared to conventional energy, but not too high. Many of them question the cost of the space infrastructure compared with the value created on ground.
- the social acceptance: even if the public is strongly motivated for the green energy, it is more and more difficult to make them accept new sites for renewable energy
- the environment impacts on animals and biodiversity, especially due to light pollution.

2.5. Multiple possible applications with DSR

2.5.1. Green electricity :

Description

Electricity coming from DSR will be produced in Europe thanks to a PV farm in an isolated area or on offshore site coupled with offshore wind farm infrastructure, that could benefit from an increased capacity factor thanks to the different intermittent characteristics of the renewable energy sources.

Major benefits identified by stakeholders

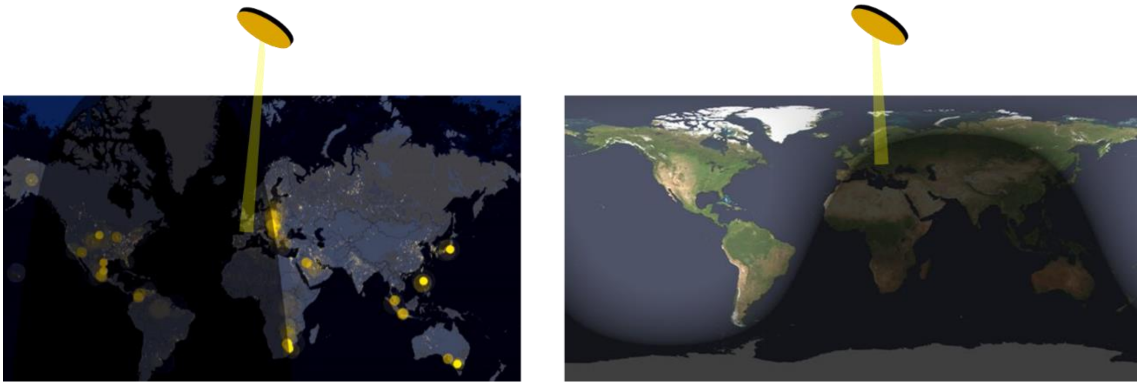
This solution could stabilize and facilitate the transport of electricity when the grid is congested, by switching from one PV plant to another.

The DSR concept becomes interesting if it can timely start and stop and can direct the sunlight on multiple European sites in sequence.

For example:

- The spotlight created by DSR could add additional hours of sunlight during a complete day (24/7). In Europe, considering the requirement of population and environment impact, it will maybe be possible to add 1 or 2 additional hours of sunlight before dawn and after dusk. It could focus on a PV farm to increase the electricity production at sunrise and sunset when the electricity demand is at a peak in the whole Europe.
- It could be also maybe interesting to increase the light on specific area where light is the most valuable by DSr stations serving multiple sites across Europe. A space station could propose light at the West of Europe during the early morning, because in the East

there is already sunshined. Like this, the West has some additional hours before the natural sun period starts. Vice versa in the evening. The DSR directs the sunlight to the East to produce some hours of artificial sunshine although the natural one is already down.



Key points to consider for stakeholders

Electricity in base load will be in competition with utility-scale PV, during regular hours where the sunlight is producing in normal conditions.

It should be investigated if the DSR concept is less expensive than electricity + storage during peak hours.

Key requirements for a competitive solution

Depending on the location, the PV farm should be limited to 500MW up to 1 GW to avoid too much perturbation to the grid (especially in case of outage).

To limit environmental impact on biodiversity, human, and animals, propositions are done to limit the light exposition after 21:00 and before 7:00 if the spot size is not contain on a reduced and isolated area. In order to confirm the propositions made by stakeholders, an isolated area (onshore or offshore) are preferable and an environmental impact study should be done to adapt this requirement.

All requirements are listed in chapter 6.1.

2.5.2. Green molecules as e-fuel, Hydrogen, Ammonia :

Description

This use-case investigated how to produce green molecules (H2, CH4, CH3OH, NH3…) with the DSR concept, using the illumination to produce the molecules, either directly by the protons to generate the chemical reaction, or by generating electricity that will be used to activate the reaction.

Major benefits identified by stakeholders

Producing hydrogen and/or capturing carbon to convert them into other energy carriers such as the molecules mentionned is beneficial when electricity is present in excess and the grid connection is not developed.

However, Hydrogen requires costly conditions for storage and transportation. A solution outside Europe is to make use of a global value chain on other more easily transportable energy carriers, perhaps ammonia, which could be converted into the hydrogen value chain in Europe, even if it will involve a significant efficiency losses.

Green e-fuels could be seen as an option rather than a solution. In any case, producing e-fuel needs to produce hydrogen first.

On the ground segment, research on new technologies is currently done. Solar panels which are able to convert sun in Hydrogen directly with high efficiency is one of the most promising solution expected to be developed by 2030[1]. Deployed in Spain (or other countries close to Mediterranean sea) is a huge opportunity. Completed with the DSR Concept on a continuous day (24/7), the technology could have a great potential.

Key points to consider for stakeholders

The best location is to be near a factory, a refinery, a pipeline, a harbor …in Europe or outside Europe. The choice of the molecule will depend on the location and the already existing installations and logistic infrastructure. Providing the basic molecules to produce H2, CH4, … is mandatary (access to water, biomass, CO2 capture…)

An isolated area is required if the production of molecules with the DSR system is expected as long as possible (until 24/24 hours and 7/7 days).

Key requirements for a competitive solution

In an isolated area, the illumination can be 24/7 on the ground segment

The LCOE of producing and delivering green H2 in Europe should not exceed 5€/kg

All requirements are listed in chapter 6.1.

2.5.3. Green desalinated water :

Description

Even if producing hydrogen needs to supply water that could be based on desalinized water, the energy provided by DSR could be used to produce desalinated water as final output used for agriculture or human needs.

Major benefits identified by stakeholders

Green desalinated water could be a helpful solution for hydric stress regions or to provide water for agriculture. Interesting for Mediterranean countries like Italy and Spain which could be under water stress. However today, it's very expensive and energy intensive to desalinate water.

Water transport is cheaper than electricity transport.

Key points to consider for stakeholders

Drinking water is perhaps much more difficult to deliver than water for agriculture, as it must respect much more strict safety and regulatory rules.

Technically, intermittency is not a problem to provide water. Besides, water could be produced during the night if the spotlight reflects the sun in an isolated area or to an offshore PV plant. However, according one interviewee, the offshore PV plant should generate a

[1] *https://newmobility.news/2023/05/08/spanish-to-produce-green-h2-under-one-euro-only-by-using-sun/*

required amount of electricity (about 5GW of electricity was proposed by a stakeholder) to get critical size. This minimum power generated depends on the location and the economics.

Key requirements for a competitive solution

No specific requirements have been identified

2.5.4. Green Heat :

Description

Green heat provides water or steam at hot temperature and high pressure from a ground focus solar radiation (for example). This one could be deployed in Europe with the DSR concept.

The green heat is currently used to produce electricity. It is also deployed with hot steam or water for industrial processes, carnot batteries and/or for thermal water desalination. Light is converted in heat or hot water which could be used in a heat network.

Major benefits identified by stakeholders

Several processes are already existing nowadays with heat networks. One of the main benefits, is to use the heat when it is available and store it for later with canot batteries when the production of heat is stopped.Heat networks are usually developed close to cities to reduce the electricity consumption and to heat buildings and swimming pool water

Key points to consider for stakeholders

The proximity to cities requires to limit the light pollution which will become a major concern for human.

Therefore, this output is not perceived as a feasible solution

Key requirements for a competitive solution

No specific requirements have been identified

2.5.5. Green Warming :

Description

Green warming results from the sun radiation. It could provide water at low temperature and low pressure.

Green warning could be deployed in Europe during winter or in areas impacted negatively by the climate change.

Major benefits identified by stakeholders

Its goal is to reduce the freezing on vineyards or on agriculture during the frosty night of winter or spring.

Key points to consider for stakeholders

It's not a permanent solution but it could be an option developed with the DSR concept if it's possible to allocate the spotlight with great accuracy.

Key requirements for a competitive solution

No specific requirements have been identified. However the impact of green warning could be evaluated during an environment study if this output is pre-selected.

2.5.6. AgriPV :

Description

AgriPV is an interesting use-case that combines crop growth with PV production. The objective is to identify synergies between the PV design and the micro climate conditions required by the crops. In some cases, the panels are composed of glass carriers which are partially covered with silicon cells, producing electricity and allowing UV-light passage for food production. Adding light during other moment of the day could lead to new use cases for AgriPV. In other cases, the panels are presents in the border of the field and could be flexible to adapt the electricity production and the growth of crop .

Major benefits identified by stakeholders

Increasing the Illumination will have an impact on the micro climate located underneath the AgriPV installation, leading to possibly new combination of Pv design and crops.

Another benefit compared to PV farm is to possibility to extend the number of potential sites in Europe, as it is a key bottleneck to select and deploy a new site in Europe at a large scale. Deploy AgriPV in existing agriculture field can be an attractive solution if spot size is compatible to avoid any illumination on people near the field.

Key points to consider for stakeholders

Electricity production is less efficient because it’s not possible to deploy PV panels on the whole field. The DSR concept could illuminate crops on a longer timeslot resulting in 100% food productivity and increasing electricity production by 100% and more if the light is reflected over extended hours.

This solution could be developed in Europe where ground is scarce. However, it’s not a continuous solution because some crops need light to grow but they also need a period of darkness in order to properly develop.

Key requirements for a competitive solution

The maximum illumination period is not well know and should be investigated.

2.5.7. Enhanced crop

Description

Quite permanent illumination on field with enhanced crops could be solution to increase production for e-fuels.

Major benefits identified by stakeholders

The ligh will permit to increase the field production, thanks to extend the duration of the photosynthesis.

As e-fuel needs crops as intrants, the forecast of production generate an imbalance to lack of intrants. Accelerating the production of crops with extended illumination could contribute to fix this issue.

Key requirements for a competitive solution

The conclusions are the same for Agri-PV.

2.5.8. Permanent or extended ligthing :

Description

Permanent or extended (public) lighting during the night for touristic zones, industrial area… could be a solution with the DSR concept. It could reduce the electricity consumption and lightning cost (more specifically for tourist areas).

Major benefits identified by stakeholders

The light intensity could be equivalent to an illuminated street at night with a full moon or meet other criteria as defined below.

The timeslot will be decided at the convenience of the stakeholders.

Key points to consider for stakeholders

Hereafter, ranges of illuminance levels in lux used for several situations and associated norm are listed :

- Public lighting (Norm EN13201)
    - Pedestrian zone in town: between 5 lux and 15 lux
- Lighting of outdoor workplaces (EN 12464-2)
    - Airports: between 20 lux and 50 lux
    - Petrochemicals and hazardous industries: between 20 lux and 100 lux
    - Railway areas: between 10 and 50 lux
- Outdoor sports lighting (EN 12193)
    - Athletics: between 50 and 500 lux depending on the level of competition
    - Football, Rugby: between 75 and 500 lux depending on the level of competition

This output could be a spin-out of any selected use-case, but probably not strong enough to stand alone.

Key requirements for a competitive solution

The maximum lightning period is not well know and should be investigated. Besides, the gain between the electricity not consumed during the night and the cost of the light produced by the DSR concept, should be analysed.

2.5.9. Other solutions :

Other solutions have been suggested :

- Green cooling : to complete the solution of Green warning. Green cooling is based on two approaches: using natural refrigerant and maximizing the energy-efficiency on buildings and equipment to reduce gas emissions from refrigeration and air conditioning. The heat that is produced is captured and used to run a thermal cooling cycle, which produces cold as the stirling engine.
- Concentrated Solar Power (CSP) with molten salt consist of an array of many parabolic mirrors which capture the sunlight and reflect it to a focus point where the heat is absorbed by a medium (for example molten salt). Temperatures up to several 100°C at the focal point are achievable, which allows to drive a classic thermal heat cycle (usually employing a steam turbine for conversion to electric power). The total worldwide capacity amounts to 6800 MW in 2021[2].
- Concentrated Photo-Voltaics (CPV) is a ground photovoltaic technology that uses lenses or curved mirrors to focus sunlight onto small, highly efficient solar cells. This leads to smaller cells, and higher efficiency per square meter as compared to normal crystalline silicon panels. However, the technology is not continued since the price of silicon panels has experienced a fast price drop making the overall cost of silicon panel installations lesser. In 2016, about 350 MW was installed worldwide[3].

Both CSP and CPV often employ tracking systems to enhance the output yield. These technologies are mature but not competitive in all situations.

2.6. Multiple possible locations with DSR

As described at the beginning, the use cases are based on outputs but also on the locations of the plant, due the constraints on the illumination period and the spot size, that strongly impacts the potential public acceptance, which is identified by all stakeholders as the main potential bottleneck of the concept.

2.6.1. Inside Europe

The interviews highlighted that locations in Europe don't have the same requirements/needs. Each country has specific infrastructure, regulations, mindset and culture. This is shown in the figure bellow.

This European map presents a synthesis of the main outputs/needs discussed with the stakeholders and feelings about possible SBSP solution.

[2] https://www.solarpaces.org/wp-content/uploads/Blue-Book-on-Chinas-CSP-Industry-2021.pdf
[3] https://web.archive.org/web/20170211082621/https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/2016_02_09_CPV_Report_ISE_NREL_Version_1_2.pdf

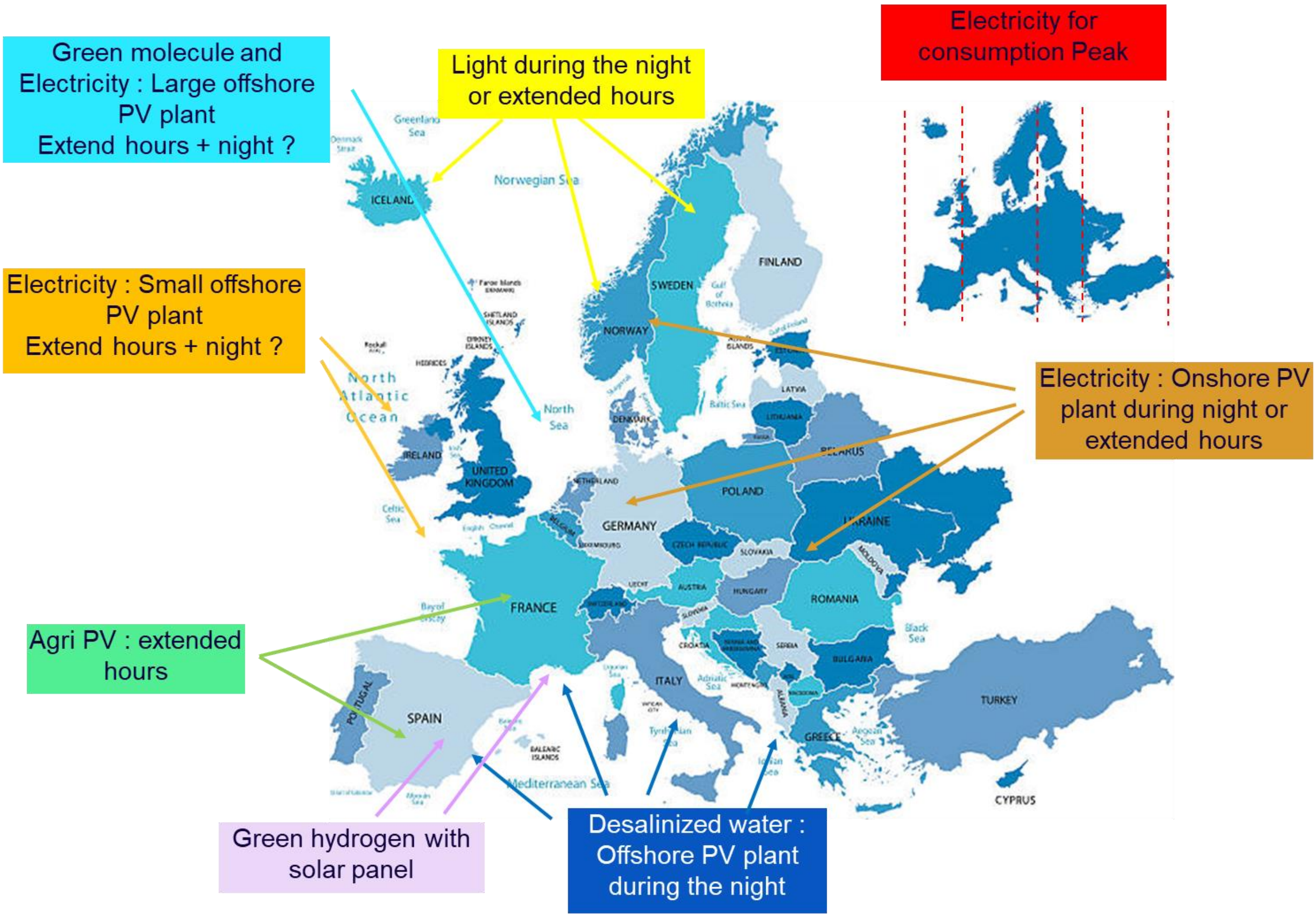


Figure 4 : The European countries and their needs

2.6.2. Outside Europe

All the applications studied outside Europe should integrate a commercial use in Europe. That's why, the solar energy is transformed, stored in renewable energy carriers and then delivered in Europe.

Regarding these requirements, electricity is an output which is not interesting outside Europe. Indeed, the PV panels will benefit from favorable conditions to produce electricity in countries near the Equator (North of Africa for instance). However, this electricity has a long way to go to achieve the European grids and energy losses will be significant in a grid.

The most interesting use case outside Europe with a commercial use in Europe is Green molecule. The non electric energy is 80% of the worldwide energy market with a majority of fossil energy. [4]Large PV plants could be installed (or are already installed) next to infrastructures (pipes, factory) for Hydrogen or e-fuels. In particular in the North Africa[5] and the Middle East countries, investment have been done (us$ 270 billions of the us$ 700 billions identified) to switch 20% of their business to solar plants and hydrogen factories. Those countries are using desertic area to implement their solar farms. Without major changes, those huge investments on ground can be directly fed by DSR that could

[4] https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf
[5] https://www.atlanticcouncil.org/blogs/energysource/realizing-north-africas-green-hydrogen-potential/

potentially double or triple the productivity. Only the transport cost should be added to the production cost.

The producers of green molecules which have mostly planned to sold to European market, are already in place and have the money to pay for "artificial sun" during 24/7.

Location could also be polar site (Antarctic,…) or uninhabited area closed to equator presents under the orbit of the mirror Geopolitical matters should be studied in order to reduce the dependence of Europe.

3. SWOT analysis of the DSR concept

In this chapter a more detailed analysis is performed on how the needs on output can be satisfied by the DSR concept. The different benefits and challenges are discussed in more detail.

A SWOT analysis is performed to give an overview of the position of the DSR concept after the stakeholder interviews. The information presented below can be used to challenge the use of the DSR-concept on the requirements afterwards.

3.1. Strengths

One of the main strengths of the DSR concept is the **inherent flexibility** present in the output of sunlight. It is applicable for a variety of applications, and can be converted in different energy vectors. This aspect especially comes to play when already considering the different scenario's to be assessed in this first analysis, where besides green electricity, green thermal merit and green molecules also hybridisation of light for agricultural applications is a possibility. Hence the entire solution can be optimized to benefit maximally from the presence of additional sunlight in a specific area.

Hybridization of different technologies for production and conversion is an important leverage to equally reduce the levelized-cost-of-energy, for new installations, but also for existing installations. The reasoning here is that enhancing existing installations is equally a viable option to explore. Making existing infrastructure more profitable can with this concept easily be achieved as well, if correctly assessed with the cost of construction and exploitation of the space-based system.

It can also be **deployed in the mid-term (by 2030),** because some technologies developed on terrestrial level are already in a high maturity state and can be upscaled in a reasonable timeframe to be suited to match the power range of the solution, which will go in the 100's to 1000's of MW. At the ground station, the technologies above mentioned in applications (cf 2.5) are sufficiently high in TRL level today to scale them up to the required power levels in the mid term. For instance, PV panels are already existing and continue to improve to maintain high efficiency during a longer life cycle with new materials... An other example which is interesting and with a rapid development is floating PV. Currently the technology is well developed for lakes and smooth water surfaces. It should be investigated to be deployed on ocean with waves.

3.2. Weaknesses

The main weakness of the DSR concept is the **large spot size**, which varies from 10 to 300 km in diameter for the envisioned power levels, depending on the altitude in orbit and partially to the size of the reflecting structure in space. This is due to the fact that a divergence of the beam is present and related to the distance between the sun and the Earth. For a non-focusing reflector, the size of the illuminated spot can be approximated by[6]:

[6] *Mirrors in the sky: Status, sustainability, and some supporting materials experiments - ScienceDirect*

$$A_{Earth} = A_{reflector} + \frac{\pi}{4}(\alpha * h)^2$$

The value of α is approximately 9.3 mrad, and is based on the diameter of the sun and the distance of the sun to the Earth, which makes it a constant. Positioning of a non focusing reflector, as an example of 100 meters in diameter in LEO (400 km) results in a spot size of 4 km in diameter, while as positioning the system in GEO (35786 km) results in a spot size of 332 km. The choice of the type and height of orbit is hence crucial for the ground application. In the next steps, a more detailed analysis will be performed with more complex mirror shapes leading to more accurate estimations.

Next to that, it has also to be considered that illumination of an area beyond the natural background illumination periods inevitably has an **effect on the environment and wildlife.** Depending on the location, the consequences could be severe with detrimental effects that spread beyond the zone of illumination. A carefull assessment is needed for specific proposed sites, with possibly counter measures to be taken to reduce the effects of the impact.

The main effect of the beam divergence is the reduction of the light intensity as compared with natural sunlight. Therefore, the added light intensity at the illuminated spot-size, will not reach the same intensity as natural daylight.[7] Hence, the light will added to the existing light intensity and can increase the lighting period at dusk and dawn. The intensity of light needed to start producing energy with commercial PV panels varies between 100-200 W/m² according to Laborelec solar experts. Hence, sufficient amount of light needed to stabilize the PV production and to be profitable as well. Ideally, to attain nominal (watt peak) PV production, a light intensity of 1000W/m² at a temperature of 25°C is required.

The sunlight that will be reflected experiences the same phenomena as natural sunlight that reaches the Earth surface in normal conditions. This means that reflected light will equally encounter **cloud coverage, and natural attenuation**, for example due to angle of incidence on the Earth surface. This reduces equally the total yield on Earth compared to the total captured energy in space.

Finally, the ground system **requires the presence of infrastructure to connect the output** to the user. This is especially a critical requirement when opted to produce green molecules. The shipping of these molecules will require large logistic facilities (harbors, pipelines) to transport them to Europe and/or global consumers.

3.3. Opportunities

Existing sites and new ground installations could be deployed regarding the trajectory of the mirrors' orbit in order to have a profitable solution (and depending on the chosen spatial solution).

The positioning of the ground station can be chosen in a **wide geographical area**, which in connection with the above-mentioned elements gives a big number of choices. Also, offshore sites can be considered, as they offer the possibility to connect the ground-based system to offshore wind parks and their respective connection hubs, which are in range for

[7] *To be further developed: how much of the light will remain ? is the amount of Lux on the ground in linear proportion with the size of the mirror ?*

the power requirements, provided that existing windparks offer sufficient free connection capacity.

As the system is based on solar energy, it is a **renewable energy production site** and it will be considered for green premium mechanisms, as it is a contributor to lower the overall carbon footprint of the European Union.

The versatility of applications can also allow the **exploration of new technologies**, and additional uses which are now covered by existing energy consuming technology. One of such applications is the provision of artificial public lighting in specific cases. Industrial sites, tourist attractions, or outdoor sport accommodations, which currently depend on existing standardization are among the possibilities.

3.4. Threats

An important threat to this concept is the **resistance of the public**. Due to concerns mentioned above, ecologic lobby groups are expected to oppose the creation of these concepts. The astronomy comnmunity will also not be in favour of the concept. Depriving areas and inhabitants from darkness at night is seen as highly impacting and not accepted in general. Risk averse decision making can result in a blocking point to obtain the needed approval and permits.

Geopolitic positioning of decisionmakers could equally favor alternatives which are to be deployed on the European continent, instead of on locations outside of Europe near the equator for example. The positioning of crucial infrastructure abroad is a serious security risk for the provision of energy for European consumers. Concerns over security of the operation of systems, especially the space based systems, are equally important to be assessed and covered from a design perspective. This equally includes the potential to weaponize this system.

The economical profit to be realized with this system is equally important. The output of this system should be competitive with existing renewable energy production sites. In the subsequent business case analysis, market evolution and expected evolution of LCOE of these other renewable technologies should be considered in the comparison with the concept.

4. Pre-selection of most promising use-cases.

The interviews enable to eliminate some outputs, as described in the table below, showing clearly that most stakeholders highlight electricity and molecules as most promising ones.

Output	Selected as one of the two most promising outputs
Green Electricity	8
Green molecules	8
Green desalinized water	1
Green heat	
Green warming	
AgriPV	1
Enhanced Crop	
Permanent lighting for human	

Table 5: The most promissing outputs

However, one of the major benefit of the DSR concept is to be used for several outputs as described in the chapter 2.5. Depending on the coming studies, the feasibility and the flexibility of the DSR concept would probably enable to combine several solutions and improve the profitability.

In terms of ground location, the following findings are been identified:

A/ Outside Europe, according to providers, distributors and consumers, delivering electricity to Europe is not an interesting use case. Electricity transport on a long distance is not competitive due to the energy losses.

Even if the production of electricity benefits from favorable conditions outside of Europe, the grid and the electricity demand should be studied and surely deployed.

B/ Near Mediterranean sea, the SBSP concept remains to be studied between extended hours and permanent solutions because:

- The sun is already present on a long period with ideal climate.
- However, infrastructure is missing (connections, …) to produce Hydrogen or electricity in huge quantity.

The SBSP concept could be interesting with investments and operations during the night to produce electricity, water or green molecule. It will depend on the location and the associated population acceptance.

The interview led to identify the main outputs and define the main requirements for stakeholders for space design of the mirror satellite.

As described in the previous chapters, a segmentation analysis is done in this section to make the comparison between the different use-cases and qualify them in terms of fitness for use within the DSR concept. The Table 6 can now be updated with the key issues

Output	Europe On Shore	Europe Offshore	Outside Europe
Green Electricity	**Where to find new plant locations for the required scale?**	**How to deploy large PV farms on sea? Rather than competing with offshore wind, is it possible to leverage permitting areas with offshore wind&pv?**	No real interest to produce electricity for European market. Producing electricity outside Europe should be evaluated taking into account the electricity demand and grid deployment.
Green molecules	Depends on the Hydrogen production plants deployed in Europe with dedicated solar farms and grid infrastructures. No real interest as the grid connection is possible	**How to deploy large PV farms on sea? How to ensure sovereignty of Europe? Is it better to convert H2 on sea or on earth? Does the limitation to extended day illumination be compensated by reduction of the logistic costs (compare to the outside Europe use case)?**	**How to supply water at large scale to produce H2? How to ensure sovereignty of Europe? Does the limitation to extended day illumination be compensated by reduction of the logistic costs (compare to the outside Europe use case)?**
Green desalinized water	No real interest except close to sea water access	No real interest except potentially in south of Europe	**How to supply water at large scale? Is the LCOE compatible with the needs?**
Green Heat	No real interest compared to the environmental risks		
Green warming	No real interest compared to the environmental risks		
AgriPV	**How to control the space segment illumination to optimize the PV & crops yields?**	No interest	**How to control the space segment illumination to optimize the PV & crops yields?**
Enhanced Crop	No real interest compared to the environmental risks		
Permanent lighting for human	**What could be the benefits compared to the environmental risks?**	No interest	No interest

Table 6 : Key issues depending of the ouputs

The segmentation can be done in according to two main dimensions. The first axis is the way energy is transferred to end-users. A distinction can be made here between an electrical grid connection, requiring the presence or the possibility to develop the needed infrastructure in a realistic way. The second axis is the location of the production facility relative to the European continent.

A first use-case is the production of green electricity or green heat through a land-based solar plant. This production site is realized on the territory of the European mainland, and hence has access to nearby developed electrical high-voltage grid infrastructure. The produced energy immediately serves consumers during peak consumption hours and can be valorised at high prices on the market. The main challenge of this scenario lies first in the public acceptance of illumination of a terrestrial area on the heavily populated European continent. A trade-off exists in realizing this installation in a rural and preferably least-habitated area in Europe, yet close enough to existing high-voltage grid infrastructure, which is often developed closer to populated area's in Europe. In this sense, the European continent differs from other continents on Earth. Where other regions, such as the Amazon region, China, Egypt, and Equatorial Africa, often have massive isolated renewable energy production sites (such as remote hydro-electric power plants) feeding this bulk energy to distant load centers over thousands of kilometers of land-based High-Voltage DC connections, the European continent doesn't have this kind of natural resources. The European electrical High-Voltage Transport Grid was developed around the historical construction of power plants and interconnected between countries since the last century. This equally means that the requirements around the allowable spot-size area on the continent are around targeting a small area in a reliable way. This should be translated in a low-orbit system, which bring the complexity of continuous focussing and re-positionning of the space-based system. A sub-variant of this use-case is the connection of a green heat facility to a heating network, to ensure heating of facilities during cold periods. This use-case is not considered viable seen the challenges encountered as described above.

A second use-case which equally considers the connection of the production facility to the electric grid targets the deployment of the solar production units as an off-shore system. This scenario would require the development of large floating structures on the sea surface or on nearby artificial islands near the European continent. Currently, the European union is investing massively in the development of offshore wind production in the North and the Baltic sea, where it is estimated that more than 200 GW of wind energy can be captured through offshore wind farms. To bring this power to shore, many countries are in the process of strengthening the national transmission systems by reinforcing grid connections towards coastal areas where offshore wind will be connected. Next to that, more and more interconnectors are built between countries, integrating long offshore subsea cable connections to allow better distribution of the power, while benefitting local needs and market conditions. It is understood that the next step in the offshore power production development requires the interlinking of these offshore wind farms at sea through large HVDC interconnections in order to be able to transfer this energy efficiently to the needed areas. The DSR concept could benefit from this fact, because in this scenario, it would allow to connect the production site to this offshore transmission infrastructure. The benefit would be that the DSR production site can be constructed in dedicated offshore wind-farm regions in complete symbiosis regarding sea surface requirements (placed in between existing or to be constructed wind turbines). The most crucial part here is the technology readiness of offshore floating structures for solar PV production. For current technology, only very limited waveheights and water movements are allowed, reducing the current floating PV deployability to lakes and ponds. However, since the development of far-shore sea floating structures is equally required for offshore wind farms, the DSR concept can equally benefit from this. Near-shore regions with favorable wind conditions, where pilon-driven structures in the seabed support offshore wind, are nearly exhausted and not fit for ever larger offshore windturbines, now reaching power levels as much as 15 MW per turbine. The offshore wind farm business equally experiences public opposition during the development phase due to visual impact of these structures on coastal areas, pushing them further away from shore.

The third location, which is due to geopolitical reasons less favorable is positioning of the production site outside of Europe. A wide variety of locations are possible, but the most favorable is located near the equator. Countries close to Equator receive more solar radiation than the poles because it is the only region of the globe with direct and perpendicular radiation. This brings as a benefit that a geostationary orbit can be selected, making the positioning and focussing more simple. There would be no need to re-position the mirror system continuously to a great extent. In this condition, a grid connection is not an option anymore, since the existing high-voltage grid infrastructure is insufficient to bring this power to the European continent. It is not a realistic option either to consider the investment in new transmission infrastructure either, due to security and political reasons. Hence the third scenario only feasible at these locations are the ones who convert the reflected energy to green molecules. It is expected that in the considered regions public opposition would be less problematic, yet equally isolated area's where wildlife and ecological impact can be minimised are to be targeted. These areas bring with them logisitic difficulties for the production of the energy output. A logistic chain of base material and produced material is to be constructed or provided. In this way, (existing) harbours, exchange hubs and exchange pipelines are to be used or constructed. The first subscenario considers the production of hydrogen, through the process of conversion of the water molecule in to hydrogen and oxygen. Current and mature technology makes use of electrolysis. Positioning the production site near an unexhaustible water source is paramount. The production of 1 kg of hydrogen requires around 9 liter of water and consumes around 50 kWh of electricity[8], with current mature technology even requiring a high level of desalination and purity. A 100 MW PV installation, with a daily yield of 0.6 GWh of solar electricity would produce around 12 tons of hydrogen each day, which requires the provision of 120 000 liters of water per day. Next to that, hydrogen production also suffers from drawbacks, as the logistic chain of hydrogen is more difficult. The size of the hydrogen molecule brings many difficulties in the transportation, the conversion and the storage. Existing pipelines for natural gas or oil are not suited to transport hydrogen and would require tremendous investment to reconvert them and make them less prone to leaks, especially at joints. Hydrogen also impacts the structural integrity of traditional steel pipes in the long term. Conversion of hydrogen in the liquid form is also highly energy consuming and very few current shipping vessels exist today. Hence, a more considerable choice would be to opt for the synthesis of a more favourable molecule, where there are a few candidates. Green ammonia can be essential to enable sustainable food production, in addition, it is emerging as the most promising carbon-neutral energy carrier for several energy applications, such as decarbonized shipping fuel and can be essential to enable global sustanaible food production through it's conversion in fertilizers. Ammonia production from hydrogen and nitrogen through the Haber-Bosch process is currently the only method to produce green ammonia used on a commercial scale.[9] Another advantage is the possibility to capture nitrogen directly from the air, which avoids the need for nitrogen logistics. Another option is the production of green methanol through biomass gasification (biomethanol), produced from sustainable biomass sources such as livestock, agricultural and forestry residues and municipal waste. The other variant is the synthesis of methanol directly from hydrogen (produced by electrolysis) and captured carbon dioxide. [10]

When considering the production of green molecules in a fourth scenario on the European continent, the same reflection is valid as for the third scenario, whereas the logistic possibilities are much greater. When considering an on-shore system, these systems encounter equally similar public acceptance and footprint constraints as the first scenario. These systems have to compete equally with existing industrial facilities, yet there are interesting opportunities with existing industrial area's where the produced molecules can be converted immediately into products in existing infrastructure, only necessiting the creation of additional pipelines for transportation. Hydrogen as the only product from the

[8] https://www.ien.com.pl/tl_files/pliki/CPE/FAQ_final_EN.pdf
[9] Why Green Ammonia ? (Green ammonia | Yara Australia)
[10] Green methanol: the fuel that can accelerate the energy transition in shipping (Green methanol: the fuel to accelerate shipping's energy transition - Iberdrola)

DSR production site is hence a possibility. Hower this option competes heavily with the first use-case.

The fifth scenario equally consideres the production of green molecules as depicted in the third scenario, while positioning the production site in offshore European waters. Conversion of seawater into hydrogen, most probably through electrolysis, is considered to be the main application, added with the same conversion through other applicable molecules by adding additional facilities in the loop (to produce green ammonia or green methanol). This would make shipping of the produced molecules more easy. The main challenge remains the same, namely positioning of the floating offshore structures for the solar PV technology.

The four main outputs[11] (with a least one location with interest) have been estimated according to the main driver of the potential, the current market size and the expected growth - CAGR (Compound annual growth rate) for the next 20 years:

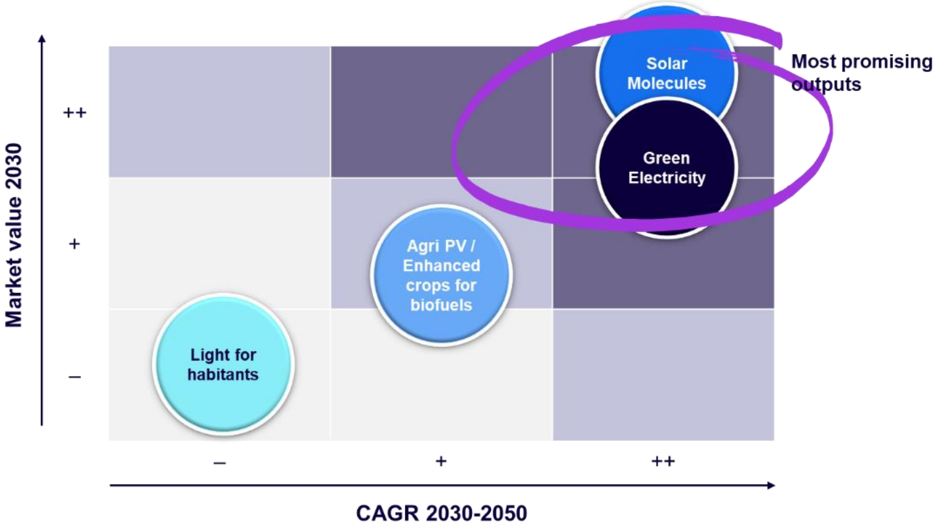


Figure 5 : outputs depending on the market size and the growth rate

The most promising outputs are green electricity and green molecule. The growth rate of electricity and hydrogen will explode in the next 20 years with the demand for transition energy and decarbonization.

These two most promising outputs will not be provided in the same way and same localisation. Their production cost will also depend on several criteria. The final choice concerning the referent use-case will be decided when the space mirror feasibility will be defined.

[11] *The lux for operators has not been plotted in the graph as it encapsulated the others*

5. Mains needs and trends

5.1. Electricity market

Today, the electricity market is mainly linked to the following needs :

- mobility
- households,
- industry
- services comsumption

Electricity is mostly produced by gas, coal, hydro and nuclear power plants.

Renewable electricity has increased since 2010 when countries has made the choice to reduce and stop their nuclear production and accelerate their energy transition with wind and PV solutions. However these energy productions are not regular and predictable.

Currently, green electricity benefits from aids in several countries to increase their development. These subsidies enable to have a price which is competitive compared to other means of electricity generations.

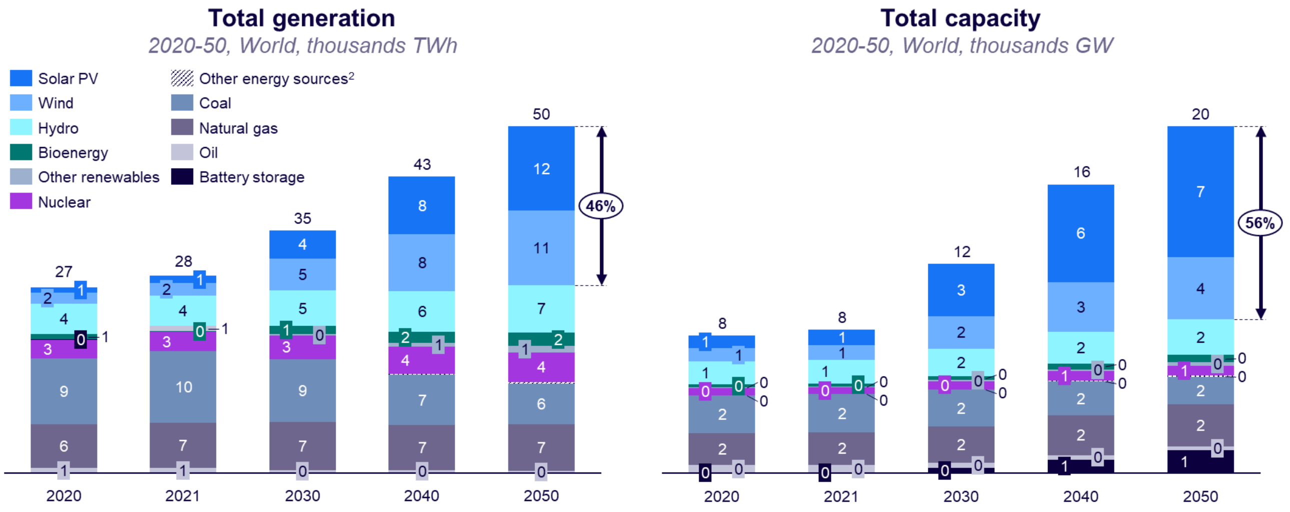


Figure 6: Electricity production and capacity

In 2050, the electricity consumption will rise by about 45%.

Solar and wind energy will represent about 45% of generation and about 55% of the global installed capacity in 2050 in the word.[13]

12

[13] *Source : based on the Stated Policies Scenario (STEPS) of IEA world Energy Outlook 2022*

5.2. Hydrogen market

Hydrogen today is mostly produced from fossil fuels (natural gas, coal). Hydrogen production accounts for 6 % of global natural gas use and 2 % of global coal use in 2021. Hydrogen is mostly used worldwide as an industrial feedstock for ammonia production.

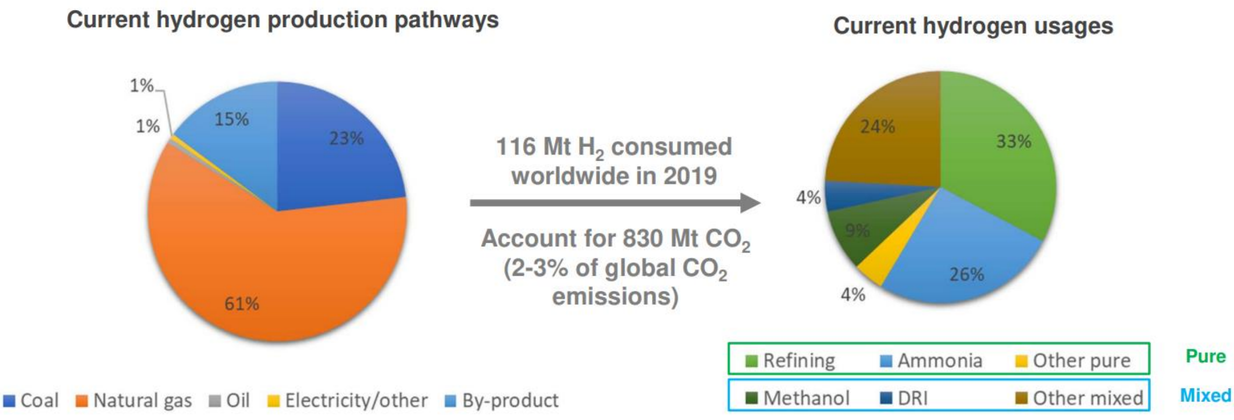


Figure 7: Current Hydrogen Use (The future of Hydrogen, IEA, 2019).

The hydrogen market development will mainly depend of three main coming applications:

- To produce heat through combustion (when mixed with methane to transport it in the existinggas network)
- As fuel for electric vehicules : using hydrogen in fuel cells, or its derivatives, in engines could decarbonize trucks, boats and planes
- For electricity production

The hydrogen demand will increase exponentially in 10 to 30 years. In order to achieve global decarbonization targets, it is necessary to sharply increase low-carbon H2-production by 2050.

Currently, green hydrogen benefits from subsidies to develop on the European market. The Hydrogen price is very low thanks to production coming from natural deposit and generation from fossil fuels and industry. The stakeholders mention that the green energy which is present in great quantity (and sometimes in excess) when the sun and the wind are present could be used to produce hydrogen and consequently reduce its cost. Many scenario's predict the coexistence of 'low-carbon' hydrogen and 'green' hydrogen for the coming 20 years and beyond. The exact repartition of the production technology will depend on many factors, including supporting policies, and local regulations, availabitlity of natural gas and renewable electricity, technology developmnets, financing, and societal aspects of each type of production.

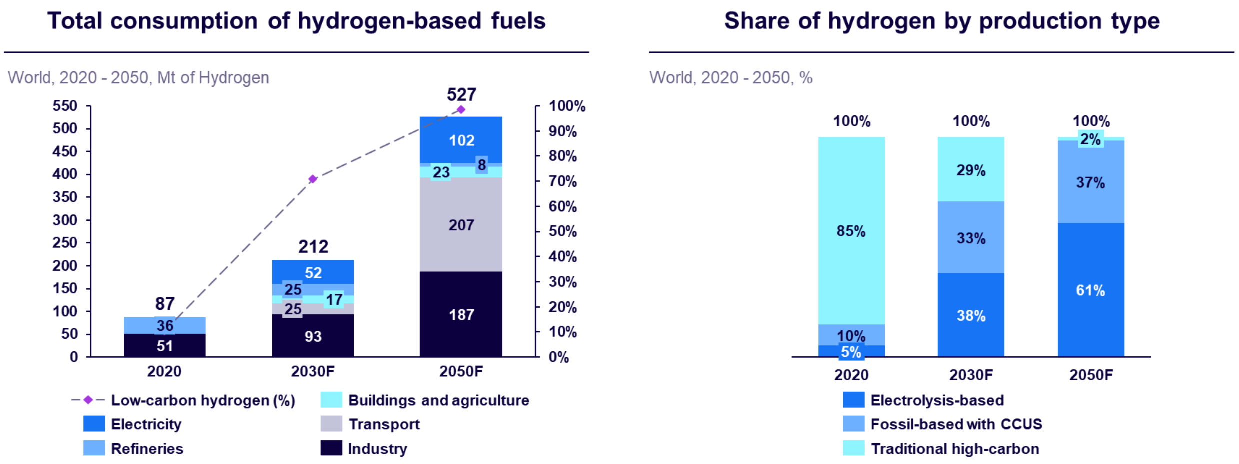


Figure 8 : Hydrogen consumption and production type

Hydrogen-based fuels' total consumption is expected to reach 527 Mt in 2050 with around 61% of it produced by electrolysis[14]

6. Major considerations on the DSR system to develop

6.1. Key requirements

A first analysis shows that some key requirements strongly impact the competitiveness/attractiveness of DSR like localization and timeslot.

Besides, the potential and urgency to decarbonize energy sector and transport sector will enable to have great progress on the ground segment. The rising energy demand in the coming years and the climate change, will also conduct to the creation of new renewables area, open minded from public and new technology development.

The following part list all the requirements identified during the stakeholders' interviews. The requirements are different if they concern electricity or molecules (hydrogen…) or others outputs. They are also classified with their technical requirements and criticality.

Technical Requirements: functional, mission, interface, environmental, operational, human factor, logistics support, physical, product assurance, configuration, design, verification. **Criticality:** mandatory, valuable, constraint

Global requirements:

N°	Requirement	Electricity	Green molecule
SBSP-SYS-001 mission mandatory	Provide electrical power for commercial use in Europe or renewable power carriers for Europe	yes	yes
SBSP-SYS-002 functional mandatory	Collect solar power in space for transfer to Ground Power Stations on Earth.	yes	yes

[14] *IEA Net Zero by 2050 report*

SBSP-SYS-003 operational valuable	The SBSP System shall start commercial operations by 2035 (TBC), ideally by 2030	yes	yes
SBSP-SYS-004 physical mandatory	The combined capability of all Space Solar Power Plants operating shall generate up to 750 TWh (TBC) per year of operation by 2050.	yes	yes
SBSP-SYS-005 operational valuable	The SBSP System shall have a nominal operational lifetime of 30 years (TBC).	yes	yes
SBSP-SYS-006 environmental mandatory	The end-of-life operations for the solar power satellite(s) in the SBSP system shall result in zero space debris.	yes	yes

Table 7 : Global requirements

Financial objectives:

N°	Requirement	Electricity	Green molecule
SBSP-SYS-007 Financial valuable	At baseload : LCOE < 30€MWh	yes	yes
SBSP-SYS-008 Financial valuable	During peak consumption : LCOE < 200€/MWh	yes	yes
SBSP-SYS-009 Financial valuable	H2 price +2/3€/kg for green premium, about 5€/kg	no	yes
SBSP-SYS-010 Financial valuable	IRR is over. 8% on the next 40 years	yes	Yes

Table 8: Financial objectives

Power and energy delivered:

N°	Requirement	Electricity	Green molecule
SBSP-SYS-011 Physical constraint	Energy received by 200W/m2 < PV < 1000 W/m² [200W/m² to activate the cells -1000 W/m² standard test for PV]	yes	yes
SBSP-SYS-012 Functional valuable	The nameplate capacity of each Ground Power Station in the SBSP System should be at least > 5GW	no	yes
SBSP-SYS-013 Functional constraint	The nameplate capacity of each Ground Power Station in the SBSP System should be at least <1GW to connect a PV plant to the grid	yes	no
SBSP-SYS-014 operational valuable	Nice to have a reliability level >99%	yes	No
SBSP-SYS-015 operational valuable	The energy production should be forecasted every 15'	yes	no
SBSP-SYS-016 operational valuable	The operation should work between 7am and 9pm and compensate the peak demand	yes	no
SBSP-SYS-017 operational valuable	The system should be flexible with market hours in all Europe	yes	no
SBSP-SYS-018 mission valuable	Localization could be in Europe with offshore sites (Floating PV, windmill farm, H2 in Europe next to existing infrastruct)	yes	yes
SBSP-SYS-019 mission valuable	Localization could be in Europe with onshore sites (PV plant in central europe, Agri PV)	yes	yes
SBSP-SYS-020 mission valuable	Localization could be on Polar site, or countries outside Europe.	no	yes
SBSP-SYS-021 Mission mandatory	The system cannot be used as a weapon	yes	yes

Table 9 : Power and energy delivered

Light management:

N°	Requirement	Electricity	Green molecule
SBSP-SYS-021 operational valuable	The system should be able to change the redirection of the light within Europe to target several plants	yes	yes
SBSP-SYS-022 operational constraint	System response time <15min (Be able to stop and start the light redirection)	yes	yes
SBSP-SYS-023 operational mandatory	System start/stop response time <15min (Be able to stop and start the light redirection)	yes	yes
SBSP-SYS-024 operational valuable	The space segment should be compliant to enlight existing PV farms	yes	yes
SBSP-SYS-025 operational valuable	The system should extend light duration (for north of Europe and winter days) from 8am to 9pm every day	yes	Yes
SBSP-SYS-026 environmental valuable	The system must avoid light pollution during night in Europe	yes	yes
SBSP-SYS-027 Interface constraint	The ground segment should be at a distance less than 30km from grid for delivering electricity	yes	No
SBSP-SYS-028 Interface constraint	The ground segment should be at a distance less than 30 km from logistic hub for green molecules	No	Yes
SBSP-SYS-029 Physical constraint	The spot size should less than 30km and ideally less than 10km	yes	yes

Table 10 : Light management

The **Error! Reference source not found.** list the complete requirements with the impact on value and the complexity to respect them.

6.2. Key performance indicators (KPI's) and success factors

6.2.1. Financial

The green electricity with the DSR concept will be a success if the cost to produce electricity is competitive with others green energies. The rising demand will lead to increasing price of electricity which will increase.

The LCOE per kilogram of Green Hydrogen is also important.

For electricity:

KPI	Target value	Comment
LCOE at baseload	< 30€/MWh	
LCOE during peak consumption	< 200€/MWh	Compared to electricity coming from PV with storage which have a higher cost of about 6 or 7.
IRR	8%	

Table 11: Financial KPI for electricity

For Hydrogen:

KPI	Price	Comment

Green H2 price	< 5€/kg	Green premium justify a cost which is 2 or 3€ more hight.
IRR	8%	

Table 12: Financial KPI for hydrogen

New technologies could reduce these prices. For instance, solar panel which convert sun in hydrogen are very promising.

IRR and Time to market is also proposed as key success factor of the DSR concept, as any source of green energy could find buyers. All stakeholders suggested "as soon as possible", "for yesterday" in terms of deadlines, showing that any incremental deployment will be strongly appreciated, typically before 2030.

6.2.2. Energy capacity and availability

For electricity, the maximum capacity and load factor are two KPI important to detail in our study.

Proposition are made to increase the load factor from 25% to 50% for PV compared to wind farm which a load factor at 40%.

Concerning the maximum capacity, stakeholders doesn't share the same requirements. They mainly depend of localization and infrastructure which are already existing. So there are propositions to 500MW and others to be superior to 1GW or 5 GW.These differences are due to configurations :

- with the grid which are differents in each countries of Europe
- which depend of the public acceptance different in all countries.

For green molecule, two others KPI are suggested:

- Annuel production capacity > 20.000 t/y
- Yield factor for H2 farm at 50-60%

Reliability and availability is an important benefit vs current solutions. Stakeholders expect to have reliability close to 99% and hight availability.

Running hours per year should also proposed as a KPI to follow these two previous parameters.

6.2.3. Technical feasibility

In terms of safety, all stakeholders expressed the need to have a limited impact on aviation and population in the vicinity of the ground station. Also a risk-analysis should be performed on the impact of failure or malfunctioning of the space based system on the ground. This should also be in line with local regulations to obtain the needed permits to be able to construct these systems. Also legal issues should be considered, and it should be clarified how existing standards can be used or adapted to integrate the requirements for these kind of systems. This also clarifies in case of legal disputes. An impact study of the space-based system on the ground should be performed.

The distance between the ground-based station and the connection point with the high-voltage transmissiong grid, when considering the use-case of a grid-connected ground-station, should be limited to no more than 30 km to be able to remain cost-effective.

When considering the use-case of producing green molecules, for example by production of hydrogen, equally the needed base-materials have to be present with the appropriate supply chain. Positioning the production site near an unexhaustible water source is paramount. The production of 1 kg of hydrogen requires around 10 liter of water and consumes around 50 kWh of electricity, with current mature technology even requiring a high level of desalination and purity. A 100 MW PV installation, with a daily yield of 0.6 GWh of solar electricity would produce around 12 tons of hydrogen each day, which requires the provision of 120 000 liters of water per day.

6.2.4. Environmental impact

It’s important to study the environment impacts in order to have a complete public acceptance. The light increase could have impact on biodiversity, animals but also on atmosphere.

The additional sun radiation is adding thermal energy to the globe. This is actually something that human mankind does not want and wherefore we are doing the whole energy transition. Mitigation could be done by switching off some CO_2 producing processes. But looking further into the future, let’s assume there are no CO_2 emissions anymore, then we would still have the heat input by the additional solar radiation.

A complete environment study should further detailled to evaluate the impact on temperatures and radiations, and others parameters. However, the environmental impact should be considered based on the following principles:

- The light transmitted is the natural light without any transformation
- The illumination power should be limited to 1000 W/m2 (equivalent to normal light provided by the sun)
- The illumination period should vary from extended day (typically from 8am to 9pm) to 24/7 in desert

Based on that, the table below qualifies the potential impact of the light redirected by the space segment according to the illumination period, showing that the DSR concept limits potential impact thank to its nature

Environmental impact factor	**Extended day illumination**		**24/7 illumination**	
	Risk estimation	*Comments*	*Risk estimation*	*Comments*
Human health	Low	It would propose a regular day especially in north of Europe in winter with positive impact on mental health	**High**	Strong potential resistance event with limitation of power received as the light pollution

Flora and fauna	Low	Some plants and animals could be impacted if their normal condition is optimized during winter and reduced day lights	**High**	The biodiversity could be impacted, and become similar to one above the polar circle Some flora or species could have a strong development that could jeopardize existing ones
Interference in aviation and ground	Low	The light is natural and no electromagnetic interference Potential risk depending on the selected orbit some glare could appear on the horizon	Low	The light is natural and no electromagnetic interference
Launch / deployment	**Middle**	The space infrastructure weight could be optimized and will reduce the number of launches needed	**Middle / High**	The space infrastructure weight could be optimized and will reduce the number of launches needed The 24/7 illumination would need more space segments and potentially more mass to launch
Ionosphere & atmosphere	Low	The light is natural and no electromagnetic interference By adding sunlight (where otherwise would be none) also thermal energy is added to the global system.	**Middle**	The light is natural and no electromagnetic interference By adding sunlight (where otherwise would be none) also thermal energy is added to the global system.
Carbon impact	Low	The carbon generated is mainly due to the launches. Full scale DSR could help to reduce fossil energy	Low	The carbon generated is mainly due to the launches. Full scale DSR could help to reduce fossil energy

Table 13 : The potential impact of the light

Based on this preliminary study, the following mitigation actions are needed:

- Only consider 24/7 illumination in uninhabited areas.

- Propose and limit as much as possiblethe lightning pollution with extended hours. . A study onshore desert or offshore location far from coast should be key to estimate the impact on biodiversity.

- Optimize the launched weight to reduce the carbon footprint

A KPI which is proposed to follow is CO2 / MWh produced.

KPI	Target value	Comment
CO_2 / MWh produced over the lifetime of the infrastructure	TBD	
MW/t in space	TBD	

7. Considerations on operational scenarios

To select the most appropriate use case it's important to consider a feasible solution with the DSR which takes into account the space constraints and energy stakeholders requirements. Therefore, in this chapter we start to challenge the energy stakeholders' requirements with the space constraints.

The localization (in Europe or outside Europe), the expected lighting time slot, the required light intensity and the spot size are the most important constraints to define a space mirror solutions. These requirements will maybe exclude some use-cases.

As an illustration, the table below gives an order of magnitude of the spot size compared to existing country area, showing that the spot size will be the main constraint to deploy the DSR concept:

Spot size diameter (km)	Corresponding area (km2)	DSR concept design	Geographic comparable	Existing ground plant comparable
300	~70 000	GEO orbit, non concentrated mirror	Ireland (70 000 km2) Guyana (83 000 km2)	
100	~8 000		Chypre (9 500 km2)	
30	~700	SSO orbit, non concentrated mirror	Arles (758 km2)	Hornsea 2 (UK) *Offshore wind world leader (462 km2)*
10	~80		Paris (105 km2) Strasbourg (78 km2)	Mohammed bin Rashid Al Maktoum Solar park (EAU) *Future PV world leader (77 km2)* Bhadla Solar Park (India) *PV world leader (57 km2)* Benbad Solar Park (Egypt) *PV Africa leader (37 km2)*
5	~20		Lille (35 km2)	Francisco Pizarro (Spain) *PV European Leader (13 km2)*

Table 14 : The spot size and corresponding area

Based on these figures, it is possible to define the preselection of potential use cases, combining output with ground location and orbit of the space segment with the following algorithm. In fact, there are two main alternatives in terms of operational scenarios : A first option is to deploy a space segment in GEO orbit, that could be fixed relatively to a ground segment. A second option is to use a low orbit to reduce the spot size, but the space segment will move relatively to the ground segment, and the lightning timeslot will be reduced to minutes/ hours during the satellite's passage and mirrors should be reoriented. So a constellation will be necessary, leading to illuminate more than one ground plant to mutualize the space infrastructure.

Orbit vs Moveable mirror		Impossible to change the direction of the light in space*	Possible to change the direction of the light in space*	Nb of potential sites**
GEO : Is it possible to concentrate the light in GEO orbit to reduce the spot size for the European zone (less than 30 km of diameter*)?	NO	Consider low orbit		**~0**
	YES	**Potential use case 1**: for each space segment, deploy one new plant near coast of Europe, typically in existing offshore wind farm, more probably with extended day illumination	**Potential use case 2**: sell "lux" to several existing PV farms in or near Europe with one space segment	**<5**
Low orbit: Is it possible to concentrate the light in SSO (or equ.) orbit to reduce the spot size (less than 5km of diameter*)?	NO	**Potential use case 3**: deploy a group of plants for electricity in Europe (extended day illumination) and outside Europe for green molecules (24/7 illumination where possible), most probably new plants to be fully in line with the selected orbit		**<10**
	YES	**Potential use case 3bis**: deploy a number of electricity plants near the European grid or in the rest of the word if the mirror could illuminate them, most probably new plants, and green molecules plants else where along the selected orbit of the space constellation (Middle East, Asia, North America…)	**Potential use case 2bis**: sell "lux" to several existing farms near Europe and also outside Europe (plants covered by the orbit of the space constellation)	**<20**

Table 15 : preselection of potential use cases

(*) Targeted diameter & redirection of the light are defined here without any detailed study on their feasibility

(**) Number of sites are estimated based on the current largest existing plants. This number could increase in 2035 and should be re-estimated in the coming steps.

8. Conclusions

This document summarizes the different requirements that were expressed by the stakeholders during the different interviews which were conducted in the first phase of the project. The return of the interviews was sufficient to define the needed requirements. The most important requirements are :

- The green electricity with the DSR concept will be a success if the cost to produce electricity is competitive with alternative renewable energy sources. The expected rise in demand will increase market prices as well. The entire system targets a levelized cost of electricity production between 30 €/kWh (base load) and 200 €/kWh (peak load). For hydrogen production, a target is set at 5€/kg. Prices are indexed in 2023. An internal rate of return of 8 % on the next 40 years is also expected for this technology, with a short time to market (deployed and operational by 2030 – 2035 preferably).
- Regarding energy capacity and availability, several key indicators were presented. For electricity production, the maximum capacity of the production site is situated between 500 MW up to 5 GW depending on the location and the infrastructure per use-case. It is equally proposed to increase the capacity factor from 25 % to 50 % for the PV-installations. For the production of green molecules, annual production capacity of over 20.000 ton/year (hydrogen) and yield factor for H2-farms at 50-60 % are expected to be profitable. A high reliability of the installation is expected, with up to 99 % annual availability. Proximity of existing logisitic infrastructure and/or high-voltage grid connections is equally required to be able to realize a viable business, with a range of 30 km between the production site and the connection point / logistic distribution point.
- Related to the transmitted light by the space-based system, the system should target the transmission of natural sunlight without any transformation, limited to 1000 W/m² (equivalent to normal light provided by the sun at noon), and the illumination period should be limited to vary between early dawn (7AM) to late dusk (9PM), to ensure proper extension of the light produced during daytime. To ensure acceptable yield, minimal sunlight intensity on the ground produced by the system should be at least 200 W/m², to be added on top of present daylight provided directly by the sun. A correct sizing of the space-based system and selection of the most appropriate orbit is hence paramount. It is explicitly required to limit the environmental and wild-life impact and interference with human activities. An exception can be made for the use-case outside of Europe (desert), where 24/7 illumination can be a possibility. In any case, the system must respect local regulations and applicable law. The system must be secure and safe, and not be able to be weaponized. A fast response time is required to start / stop the system within 15 minutes, as this is the clock wise of the flexibility managelent of the European electricity grid.

  Based on the requirements identified by stakeholders and the constraints of the DSR concept, three main use cases have been pre-selected, described in the table below:

	Potential use case 1 GEO Electricity Provider	Potential use case 2 Lux provider for ground operators	Potential use case 3 Multi energy provider
Solar energy generated by…	A GEO space station with a focus spot size	A GEO space station with light redirection & focused spot size or a low orbit constellation	A low orbit constellation
…and collected in…	Near coast of Europe, typically in existing offshore wind farm	Several existing PV farms	Group of farms in Europe and outside Europe, most probably new plants to be fully in line with the selected orbit
…received with hours of operation…	Extended day illumination (7am-9pm)	Extended day illumination (7am-9pm) in Europe, 24/7 outside Europe	Extended day illumination (7am-9pm) in Europe, 24/7 outside Europe
…and transformed in…	Green electricity	Lux power	Green electricity in Europe, solars outside Europe
… to be sold to…	Electricity end user	Ground operator	Energy end users
… located…	In europe	Along the orbit	Mostly in europe but also in other regions of the world to maximize the space segment utilization
… for a final use in…	Electric use cases	Any output	Electric uses cases, heavy mobility, industrial processes
…allowing to …	Get clean energy without any storage needs, especially at the peak period, at a competitive price	Increase the ROCE of its ground infrastructure for a marginal cost	Get green H2 or equ. at scale instead of fossil energy Get clean energy without any storage needs, especially at the peak period, at a competitive price

Table 16: The main use cases

The development of a focused mirror is a key enabler of the competitiveness of the DSR concept and the possibility to redirect the light can offer an original business model, where it could be possible to sell "lux" to ground operators, whatever their outputs (green electricity, green molecules, agriPV…)

The competitiveness of all these use cases will depend on several factors:

- the public acceptance on the environmental impact, as it becomes a key bottleneck for developing renewable energy.
- the technical feasibility, especially to focus the spot size and redirect the light from space,
- the economics of the architecture, to get an LCOE compatible with the stakeholders' needs.