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

TN4 – ARCHITECTURE DEFINITION REPORT

REPORT TO
EUROPEAN SPACE AGENCY (ESA)

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For public distribution

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1. INTRODUCTION

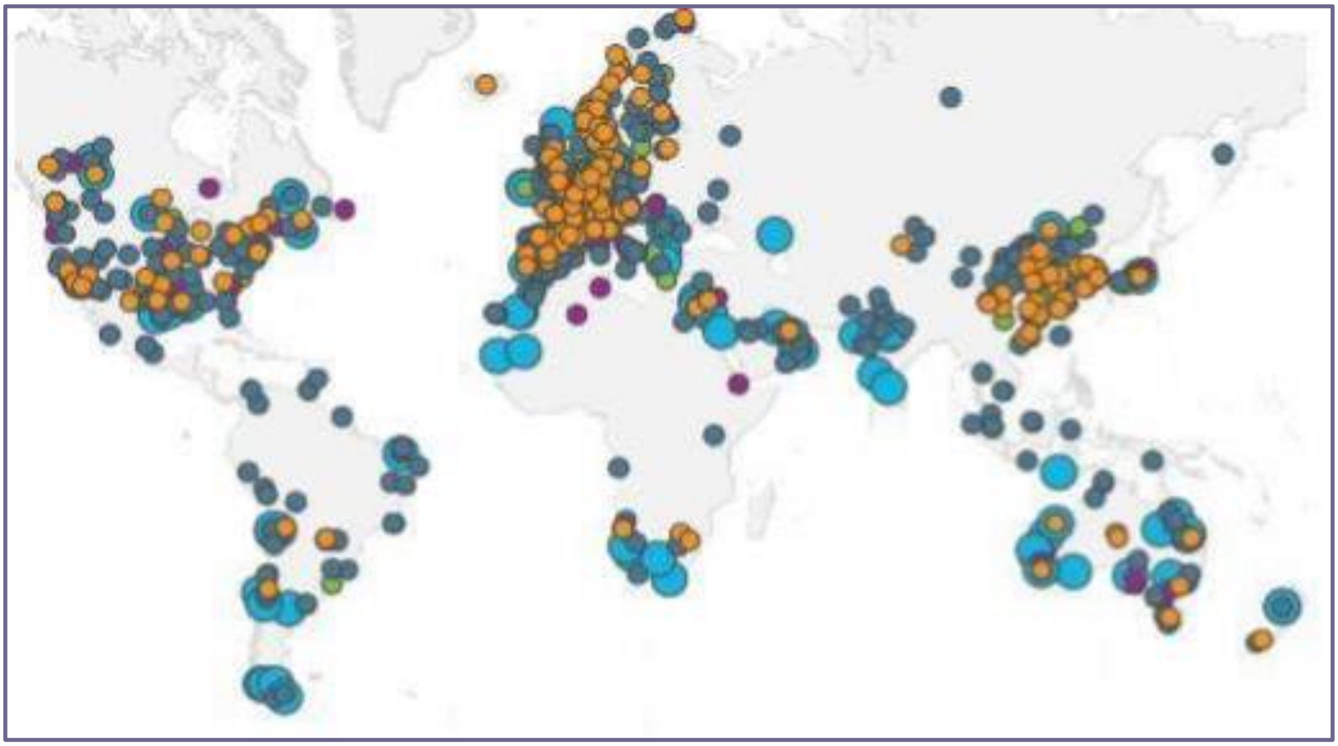
The present document describes he architecture of the DSR concept and is structured around two main parties:

- The description of the ground segment: the ground stations are existing infrastructures and should not be further designed. The RP5 document describes the key points of it : configurations, size and locations. As the output of DSR system is mainly hydrogen, the document analyzes the value added by DSR from a hydrogen producer point of view, in this cas Air Liquide,
- The description of the space segment, in the appendix 1 of this document, written by Thales Alenia Space.

2. H2 ENERGY MARKET

The World Hydrogen Energy council, created by Air Liquide and Toyota in 2017, is a gathering of large company CEOs to address the H2 Energy market. A few figures published by the H2 Council are presented below.

Significant international momentum



Giga-scale production
Integrated hydrogen economy
Large-scale industrial usage
Infrastructure
Transport

110+ Giga-scale production *(renewable and low-carbon projects)*

90+ Integrated hydrogen economy *(cross-industry, projects with different types of end-uses)*

550+ Large-scale Industrial usage *(refinery, ammonia, methanol, steel and industry feedstock)*

90+ Infrastructure *(hydrogen distribution, transportation, conversion and storage)*

190+ Transport *(trains, ships, trucks, cars and other mobility applications)*

The foreseeable investments by the worldwide industry are as follows :

~1.000 projects announced with
investments of **$320 bn**
(and a target of $610 bn by 2030)

53%
industry

18%
transport

+ large infrastructure projects emerging
(exports, pipelines)

Updated in June 2023

Whereas the investments committed by Air Liquide are here below, with a 20 MW electrolyzer operated in Canada from hydraulic power and a new one in construction in French Normandy at 200 MW.

Before 2035

~€8bn	>3x
INVESTMENT DECISION	SALES

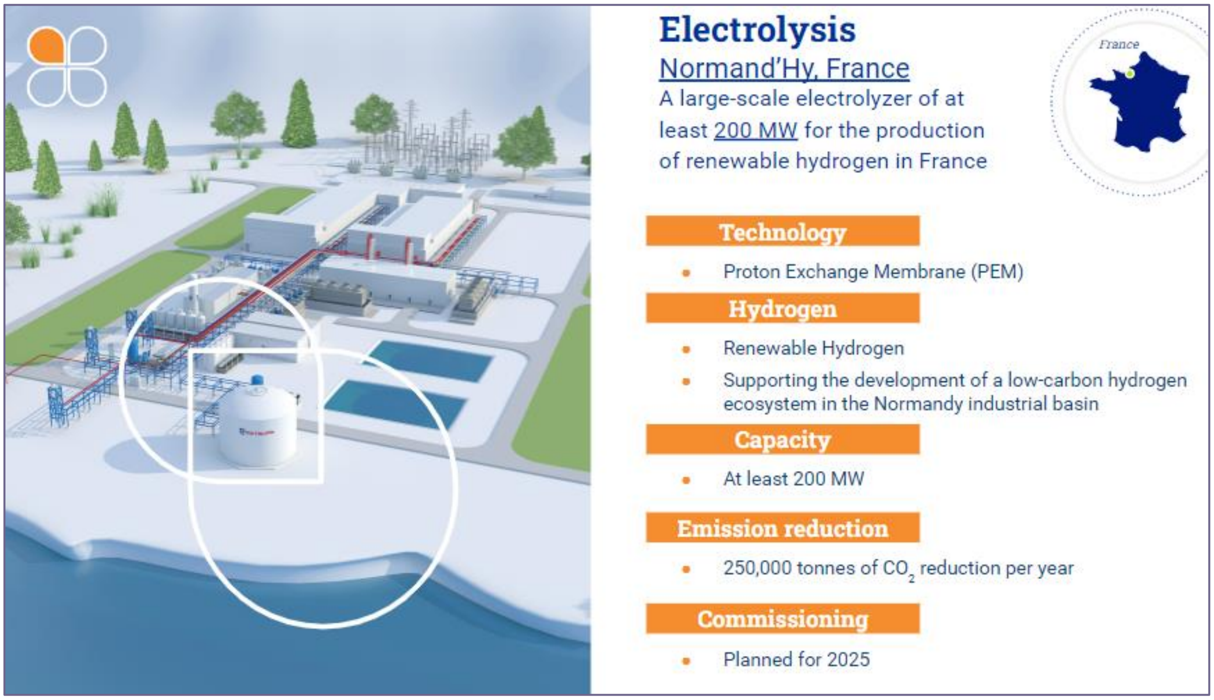
By 2030[(a)]

3 GW

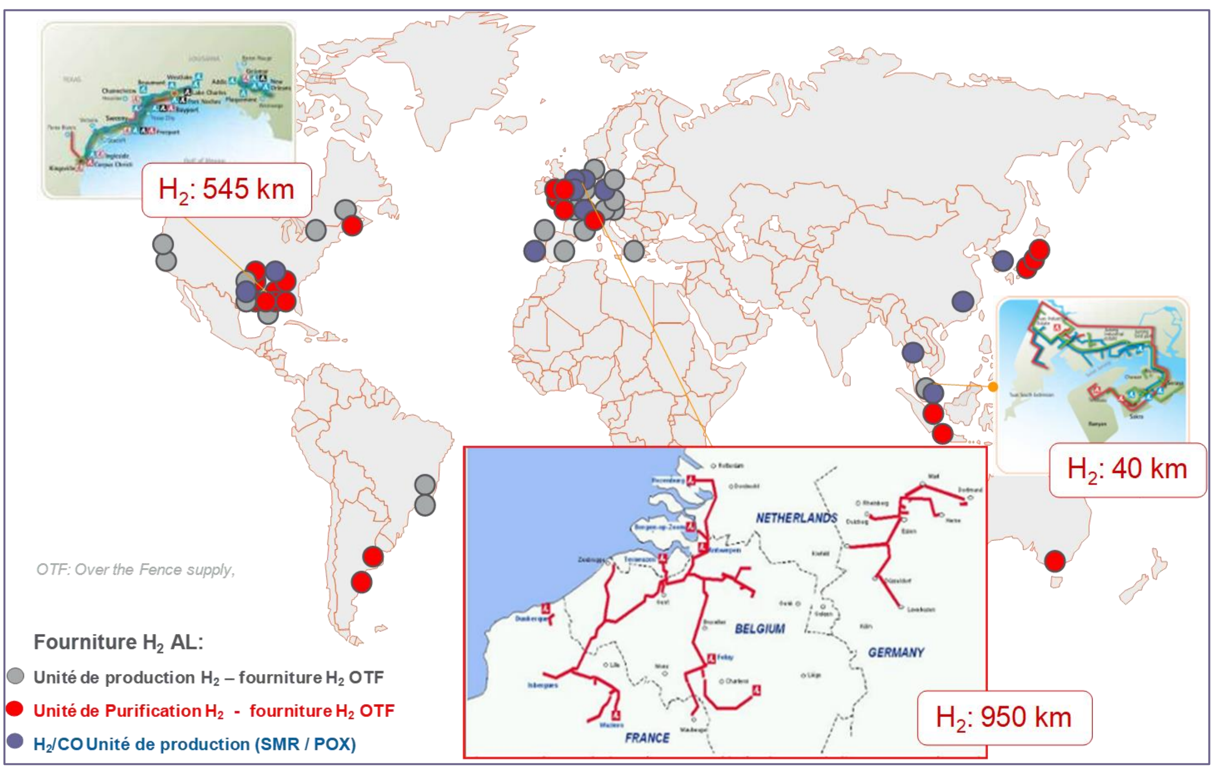
ELECTROLYSIS

(a) Including a confirmed capacity of 1 GW still under construction

Here below is a description of Air Liquide H2 production center in Normandy:

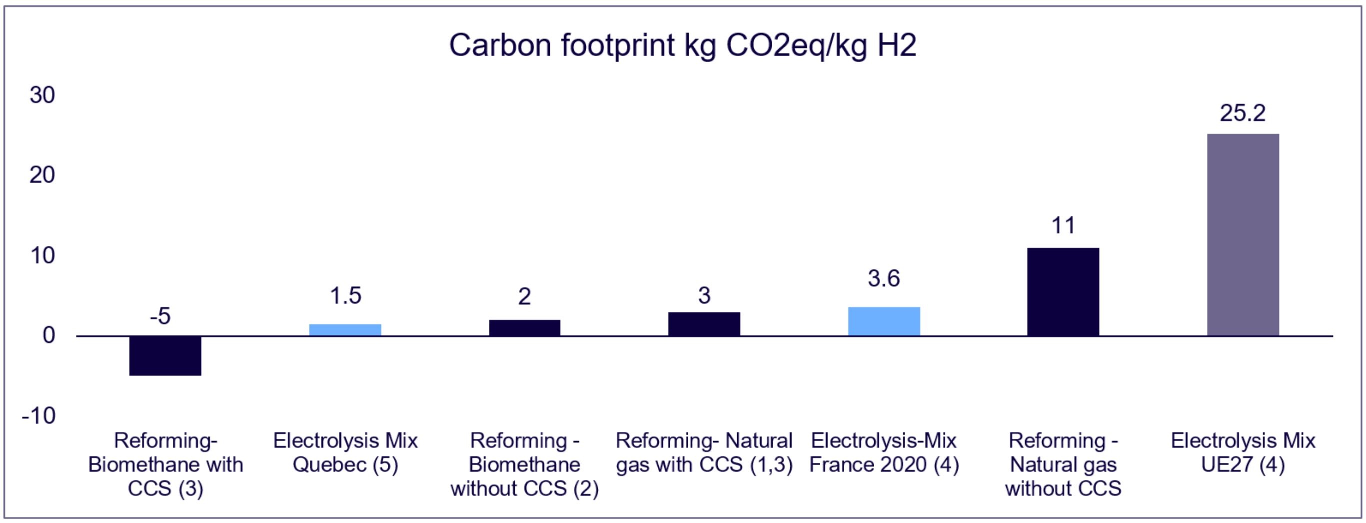


and below is a map of Air Liquide's H2 pipeline network working between 50 and 80 bars.



The graph below shows the CO2 footprint for each Hydrogen production process, in kg of CO2equivalent per kg of H2. This does not include liquefaction.

One can see for electrolysis, this can go from 24 kg CO2e/kg H2 in a highly carbonized electricity mix (such as those in Germany or Poland), to 3,6 in France (with a low carbon footprint, thanks mainly to nuclear power),and down to 1,5 kgCO2e/kg H2 in Quebec, where the energy comes from hydropower.



Carbon footprint of H2 production processes, depending on the process itself and the energy mix

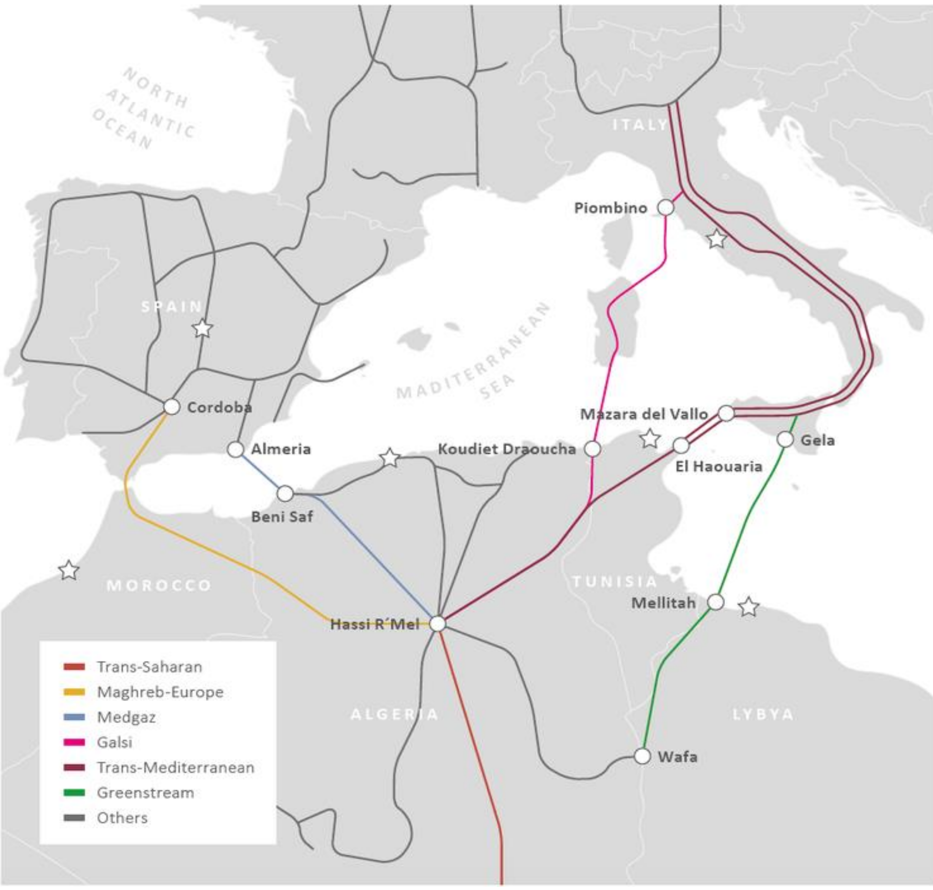
3. THE EUROPEAN HYDROGEN BACKBONE : A HYDROGEN PIPELINE NETWORK OF MORE THAN 50,000 KILOMETERS

Intended to bring together players in order to create a pan-European hydrogen distribution network, the EHB (European Hydrogen Backbone) currently brings together more than 30 energy infrastructure operators covering 29 European countries.

Responding to the objectives of the REPowerEU programme, the initiative projects the deployment of a network of hydrogen pipelines of more than 50,000 kilometers by 2040. According to projections, this future hydrogen backbone will be based on both the conversion existing gas networks and the creation of new infrastructures.

We describe here below the South H2 Corridor project, since it might be an ideal target for a Space Based Solar Power.

The Hassi R'Mel site is located in Sahara at 31° latitude, where the solar insolation is maximum throughout the year (see figure later down). Both PV and windpower will be installed in the range of 50-60 GW. It is to produce up to 4 mta (million tons per annum) of H2.



Hydrogen pipeline connecting North Africa to Europe: SoutH2 Corridor

An impressive 3 300 km Hydrogen pipeline connecting North Africa to Europe will be developed under the SoutH2 Corridor project led by Snam S.p.A. Gas Connect Austria , Trans Austria Gasleitung GmbH , and Bayernets GmbH who each submitted their Project of Common Interests (PCI) applications under the EU Commission's TEN-E regulation in December 2022.

The pipeline will originate in Algeria, in the Hassi R'mel region where Sonatrach has already massive gas infrastructure deployment, it will then pass the Algerian town of Hassi Messaoud, then into Tunisia through the town of Sfax, then the pipeline will cross the Mediterranean Sea to Italy and connect to the already existing Snam S.p.A. network and finally it will continue through Austria and Germany.

The initiative, according to the partners, is centered on the utilization of existing repurposed midstream infrastructure to convey hydrogen, with the addition of new dedicated infrastructure where necessary.

A high proportion of repurposed pipelines (>70%) will allow for cost-effective transportation, while access to favorable renewable hydrogen production locations in North Africa which will enable competitive production.

The SoutH2 corridor will be part of The European Hydrogen Backbone with a Hydrogen import capacity of more than 4 Million tons per year and is expected to be fully operational in 2030.

Link to Fraunhofer CINES study:

MENA countries can play a major role

Due to their geographical proximity, low-cost hydrogen production potential and existing gas infrastructure, six MENA countries are considered key players for realizing the REPowerEU import target: Morocco, Algeria, Tunisia, Libya, Egypt, and Saudi Arabia.

The study estimates the hydrogen demand in Europe to be about 376 TWh by 2030 and about 2,000 TWh by 2050. By 2050, Europe will be able to meet a significant portion of its hydrogen demand through imports from the six selected MENA countries. The majority of these imports will have to come via pipelines. At the same time, ammonia imports by ship will also play an important role for Europe from 2030.

Socio-economic aspects need to be considered

While MENA countries can play a very important role for the import of clean hydrogen in Europe, the authors argue that, in addition to the technical-economic aspects, socio-economic aspects and political dimensions of hydrogen deployment, including strict sustainability criteria and domestic and primary energy demand must be considered before the hydrogen export potential from MENA countries to Europe can be determined.

Germany will be Europe’s hydrogen import “juggernaut”

For Germany, the hydrogen consumption is forecast to be around 84 TWh in 2030 and 492 TWh in 2050. This makes Germany by far the largest hydrogen consumer within Europe. Since there is a gap between production and sectoral consumption of about 1.8 Mt (60 TWh) in 2030 and almost 8 Mt (266 TWh) in 2050, Germany will become a major hydrogen importer in Europe.

The table below shows the insolation in different locations in Algeria (found in the following thesis report : see link to Thesis University of Biskra):

Table 1: Potential for solar in Algeria

Rgions	Coast	High mountains	Sahara
Area (%)	4	10	86
Average illumination duration (h/year)	2650	3000	3500
Average energy received (Kwh/m2/year)	1700	1900	2650

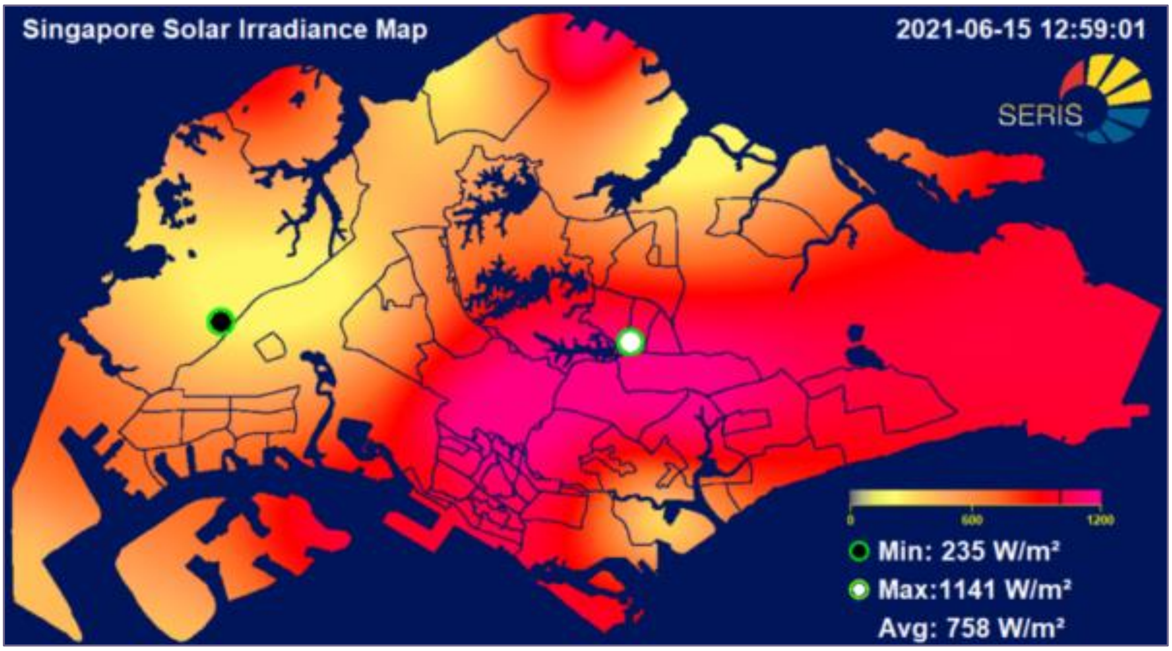
In Sahara, the average daily illumination by the sun is about 10 hours (3500 / 365 days = 9.6h) and the annual solar energy received corresponds to an average of 0,75 kWh/m2 (2650 / 3500 = 0.75), for 10 hours per day.

Therefore, in order to produce 4 MT per year (mta) of Hydrogen in the Sahara,for feeding the South Corridor2 pipeline network, we will need, without solar concentration from space, :

- To produce 240 TWh/y of electrical power in order to feed the electrolyzers (55 MWh/t H2) and pumps (5 MWh/t for pumps @ 60-80 b)
- The solar plant will peak at 68 GW spread over several plants probably
- To extract 36 MT/y of water from underground aquifer, or 1 m3 /sec
- To install about 500 km2 of solar panels (25-30 km in diameter) with the yearly insolation found in the table here above and assuming a PV efficiency of 20%

We compute in the next chapter some figures about an SBSP illuminating the PV field in Hassi R'Mel site.

Another potential site would be Singapore, where floating PV farms are already installed nearby the city benefitting from a good insolation as shown on the map below:



Insolation in Singapore

Large floating PV farms have been installed as the one shown below:

Floating photovoltaic farm in Singapore, one of the world's largest floating solar panel farms, spanning an area equivalent to 45 ha. It is equipped of 122,000 solar panels spread across 10 solar-panel island, and corresponding to an installed capacity of 60 MWp

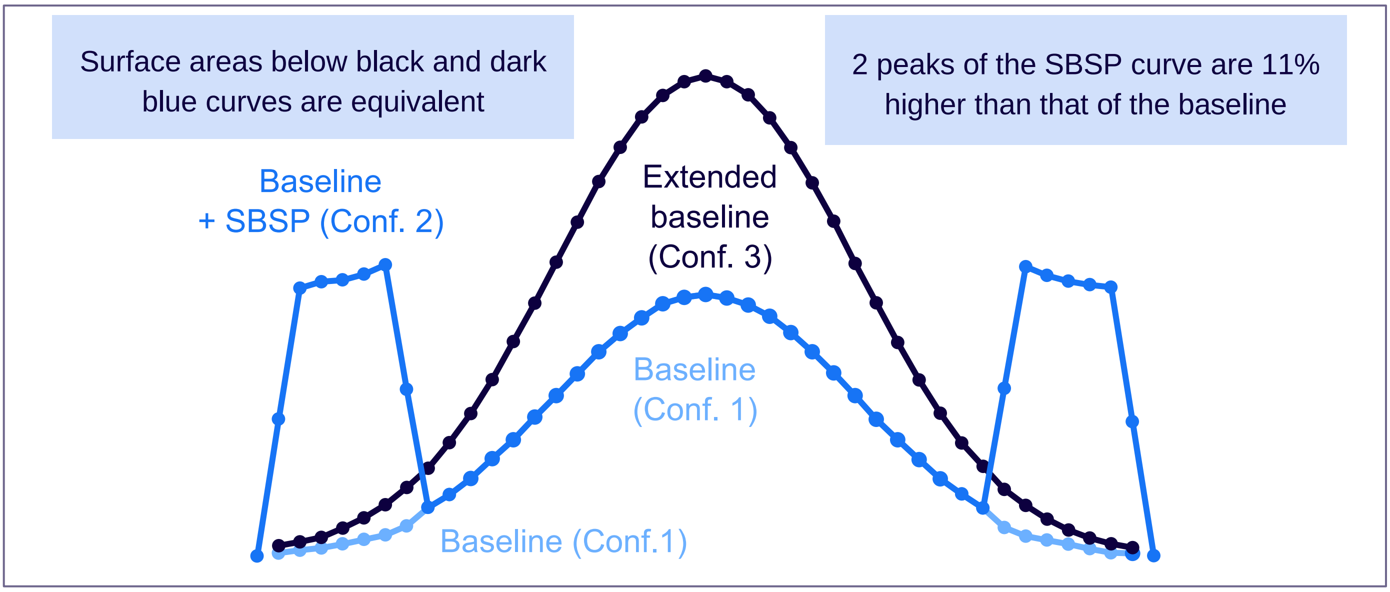
4. ELECTROLYSIS FROM SOLAR POWER: BASIC ELEMENTS WITH AND WITHOUT SPACE BASED SOLAR POWER (SBSP), THE CASE OF HASSI R'MEL

Let's try to assess in rough order of magnitude the impact of a SBSP system on both an electrolyzer connected to a PV plant and to the PV plant itself. In the analysis here below, we assume a PV farm is illuminated by trains of satellites which are cruising at medium altitudes (in LEO). We will also study, in a second part, the effect of having satellites in GEO.

4.1 CONFIGURATION 1: BASELINE PV FARM WITH ELECTROLYZER, WITHOUT SBSP

We assume throughout an ideal sunny day the natural insolation power follows a kind of Gaussian curve, as that shown on the blue baseline curve in the graph below:

- illumination starts at dawn, culminates at noon and ends at twilight (no value, since we use rough dimensionless numbers for the sake of comparison between each configuration);
- this corresponds to a given PV surface area; we assume the electrical power generated by the PV panels is proportional to this illumination curve (constant efficiency with respect to the position of the sun, which is not quite true);
- the electrolyzer must be sized for capturing all the solar power: its size, and therefore investment CAPEX is proportional to the peak power of the PV field, hence the peak of the insolation curve;
- its daily production of H2 and hence revenues for the electrolyzer operator are proportional to the surface area below the curve.
- This provides a given CAPEX/amortization ratio, hence a given Levelized Cost of H2 (LCOH) valid over the amortization period.



Daily variation of power production of a photovoltaic (PV) farm in 3 different configurations (ideal generic case, with trains of scrolling satellites)

4.2 CONFIGURATION 2-A: BASELINE PV FARM WITH A BIGGER ELECTROLYZER, ILLUMINATED BY A SBSP SYSTEM IN LEO

We keep the same PV field surface area and efficiency and we assume we just add a constant illumination power provided by the SBSP during 2 hours after dawn and two hours before sunset. This constant additional illumination is set to be equal to the natural peak solar illumination (i.e 1000 W/m2 over 2x2 hours, for the sake of clarity). This leads to the second orange curve. In this configuration of the SBSP, we have assumed trains of satellites around 800 km in altitude that move from South to North in the local sky and reverse way in the afternoon. The ramp up of additional power is very sharp: in about 10 mn it goes from zero to 1000 W/m2 once a maximum number of satellites are high in the local sky.

We also assume the electrolyzer is enlarged with respect to the baseline, so as to capture the maximum peak power.

We see the following:

- 2 hours after dawn (resp. 2 hour before sunset) the SBSP illumination (1000 W/m2) adds to the natural one and the total power exceeds by 11% the peak power at noon of the baseline configuration; in order to capture this, the power of the electrolyzer must be enlarged by 11%, hence its CAPEX;
- The surface area below the curve is roughly 1,65 times as much as in the previous case; consequently; the electrolyzer cost 11% more but produces 65% more. The LCOH is improved. Notice we have not changed the CAPEX of the PV field, and we have not added the CAPEX/OPEX of the SBSP, meaning we implicitly assume that the price of energy is equivalent with or without SBSP.

4.3 CONFIGURATION 2-B: BASELINE PV FARM AND BASELINE ELECTROLYZER, ILLUMINATED BY A SBSP SYSTEM IN LEO

We assume here the electrolyzer is equivalent to that of the baseline. It can therefore capture the peak power of the baseline but not the peak power provided when adding the SBSP. This means it roughly produces 60% more than the baseline configuration, i.e 3% less than in configuration 2A.

The excess of power above 1000 W/m2 in our example, is not used by the electrolyzer, hence has to be sent to the electrical grid. We have therefore a coproduction of H2 and a small variable electrical power 2x2 hours per day. As said before, this roughly corresponds to 3% of the energy produced by the illuminated PV farm.

Increasing the CAPEX of the electrolyzer by 11% just for producing 3% more is not interesting. It is clear configuration 2B is better than the 2A one.

4.4 CONFIGURATION 3: EQUIVALENT PRODUCTION WITH EXTENDED BASELINE PV FARM AND ELECTROLYZER, WITHOUT A SBSP SYSTEM

In this third configuration, we try to calculate by how much we should increase the surface area of the PV field compared to configuration 1, in order to get the same energy production as in configuration 2-A, but without SBSP.

We see the following:

- The peak power shall be 74% higher than that of the baseline configuration;
- The surface area below the curve is the same as in configuration 2A, by definition, hence also 65% higher than in the configuration 1;

Consequently:

- The electrolyzer will cost 74% more than in configuration 2B for producing almost the same amount
- or, if we compare to the baseline, it will cost 74% more but will also produce 65% more, hence leading to no LCOH improvement.
- Notice the CAPEX of the PV field shall be increased by 74% as well, but this will marginally reduce the LCOE (levelized cost of energy); there is of course no CAPEX/OPEX related to a SBSP accounted for, in this example.

Summary of conclusions for SBSP in LEO

The table below compares each configuration to the baseline, with respect to the amount of H2 produced and to the size of the electrolyzer (the CAPEX being proportional to the size, i.e to the maximum power of the electrolyzer).

	conf.#1	conf. #2-A	conf.#2-B	conf.#3
	Baseline	**SBSP same PV larger ELY**	**SBSP same PV same ELY**	**No SBSP Extended PV very large ELY**
Amount H2 produced	1	1,65	1,60	1,65
CAPEX electrolyser	1	1,11	1	1,74

Comparison of all configurations to the baseline

When considering the results from the viewpoint of the owner of the electrolyzer/producer of H2 only, we can see the following:

- The most promising configuration is the #2-B where the SBSP illuminates an existing PV farm equipped with the same electrolyzer:
  - It means that without additional investment on ground, we produce 60% more H2; the ROI (return on investment) of the electrolyzer is dramatically increased and hence the LCOH reduced (see chapter here after);
  - The excess of electrical energy in configuration 2A (about 3-5%) goes to the grid;

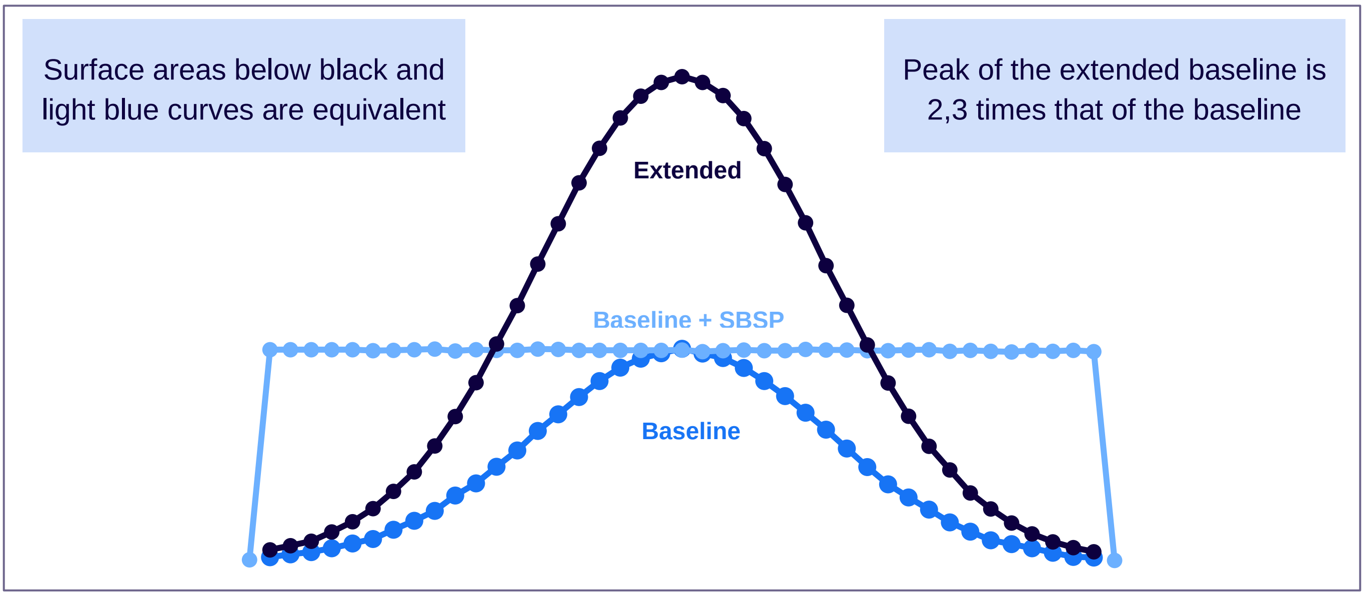
The study of configuration 3 clearly shows the benefit of using a SBSP system:

- Instead of enlarging the surface area of a PV farm by 74% to increase its production, it would be better to illuminate an existing one with a SBSP system without increasing the size of the electrolyzer.

4.5 CASE OF A GEOSTATIONARY SBSP SYSTEM (NOT USED FOR DSR BUT FOR COMPARISON)

All previous hypotheses are based on the use of satellites operated by trains and flying at medium altitude. The trains are therefore scrolling in the local sky, thus illuminating the PV site only 2 hours in the morning and in the evening.

Another option would be to use geostationary satellites that would illuminate the site during 12 hours from dawn to evening, illuminating the site in complement to the natural sunlight. The total illumination received by the PV farm is therefore set at a constant value, hence providing 1000 W/M2 over 12 hours, as shown below:



Illumination in the case of case of geostationary satellites

In that case, the surface area below the curve is 2,3 times that of the baseline. For the same electrolyzer CAPEX, we produce 130% more, thus reducing the LCOH.

Of course, should this type of geostationary satellites be implemented, their impact in terms of LCOH reduction will be much better than with the scrolling ones placed on medium orbits. Indeed, with the same electrolyzer, we will produce 43% more than trains in LEO (2.3/1,6), as shown in the table below:

	Baseline	LEO trains	GEO system
Amout H2 produced	1	1,6	2,3
CAPEX electrolyser	1	1	1

5. IMPACT OF AN SBSP SYSTEM ON LCOH

A study on the Levelized Cost of H2 (LCOH) done by the National Institute of Clean and Low Carbon Energy in China (published in 2020 in the Energy Storage Science and Technology journal, see the link :*Cost analysis of hydrogen production by electrolysis of renewable energy,* by GUO Xiuying, LI Xianming, XU Zhuang, HE Guangli), shows the weight of each cost element for electrolyzers connected to PV farms.

The LCOH is calculated as follows:

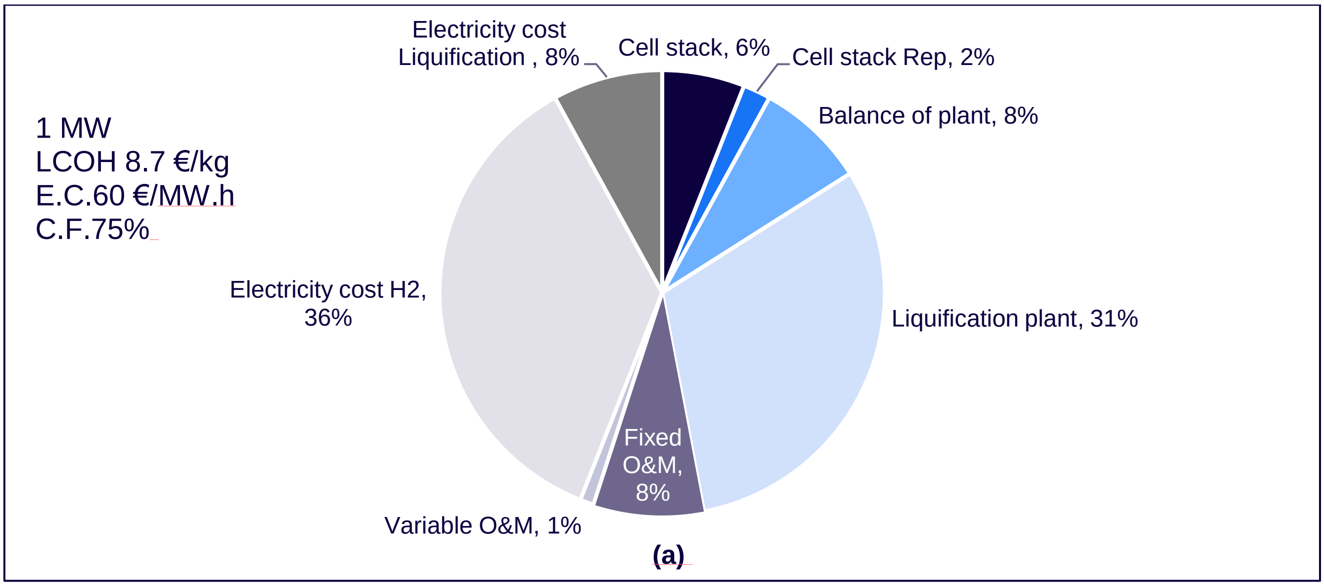
- All fixed costs incurred by the electrolyzer during its amortization period (typically 15 years), which includes the amortization costs of the CAPEX, the manpower to operate, the maintenance of the electrolyzer and any other fixed costs; Please note that figures in this chapter are based on the current CAPEX values that should be strongly decrease in the next years
- All energy costs for producing the H2 over the amortization period, which are proportional to the amount of H2 produced, including water (assumed to be negligible with respect to the cost of energy)
- The fixed and variable costs over the amortization period are summed up and divided by the total amount of H2 produced during this period.

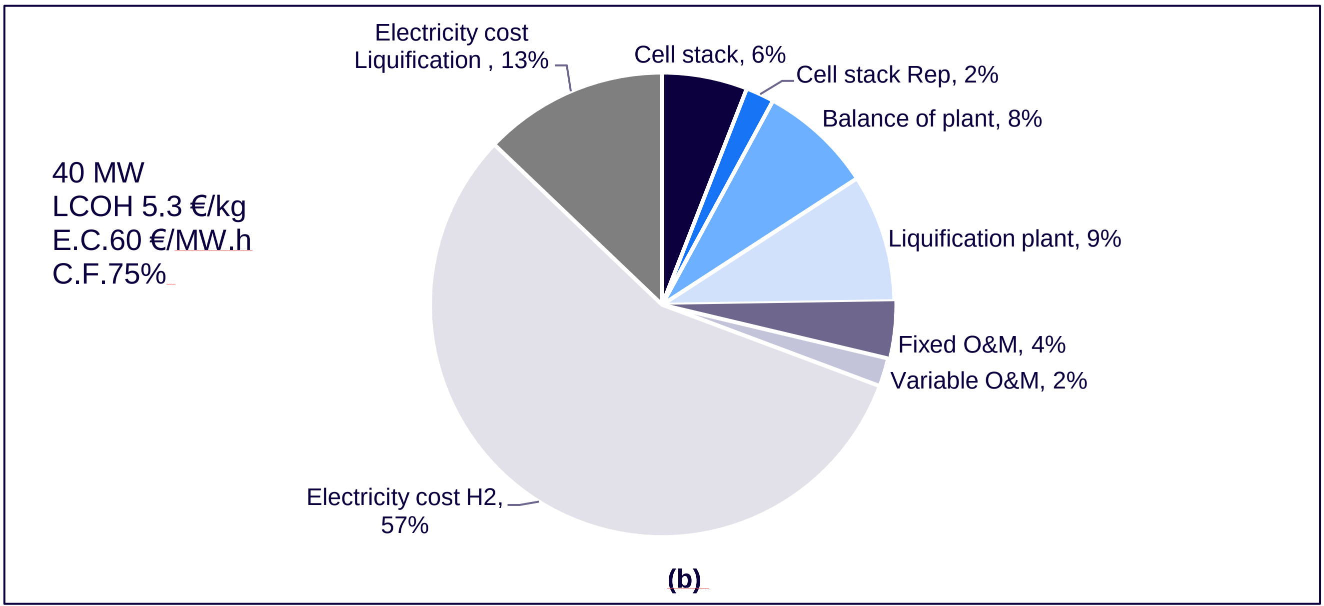
Notice we need a few dozen € to procure nine cubic meters of water, enough to produce one ton of H2 that in return will require a few thousands of € to be produced by electrolysis.

In the graph below they have compared the cost breakdowns of 1 MW and 40 MW electrolyzers coupled to H2 liquefiers. The price of energy is kept constant at 60€/MWh. The resulting LCOH is valid at the outlet of the H2 production plant. It does not include transportation and distribution costs.

For a 40 MW electrolyzer, the LCOH for production and liquefaction is dominated by the cost of energy that represents 70% of the cost of H2, including 57% for electrolysis and 13% for liquefaction, while the CAPEX/OPEX of the electrolyzer+ liquefier represent 30%. This leads to a LCOH of liquid H2 equal to 5,3 €/kg in this study. Notice O&M on the graph represents the Operation and Maintenance costs.

Since in our study case, H2 is transported by gas pipeline, we have to subtract the fixed and variable costs of the liquefaction. We end up in a LCOH at the outlet of a 40 MW electrolyzer equal to 4,03 €/kg, where energy represents 75% of the LCOH.





Cost Breakdown of H2 production plus liquefaction by electrolysis from solar power

Should the energy price be 100 €/MWh, this LCOH at the outlet of the electrolyzer would become 6,04 €/kg, where energy is 83% of the cost. These are the costs of the baseline with no additional illumination by an SBSP system.

If we are in configuration 2B above (for satellites in low orbit), we have seen that compared to a baseline, the use of an SBSP system increased the productivity of the H2 production system by 60% for the same CAPEX/OPEX (O&M cost increase due to a higher workload are certainly of a second order of magnitude, and are thus neglected). This results in a lower LCOH equal to 3,65 €/kg instead of 4,03 €/kg in the baseline. Going to GEO will result in an even lower LCOH equal to 3,47 €/kg. All this is calculated with an energy cost at 60 €/MWh.

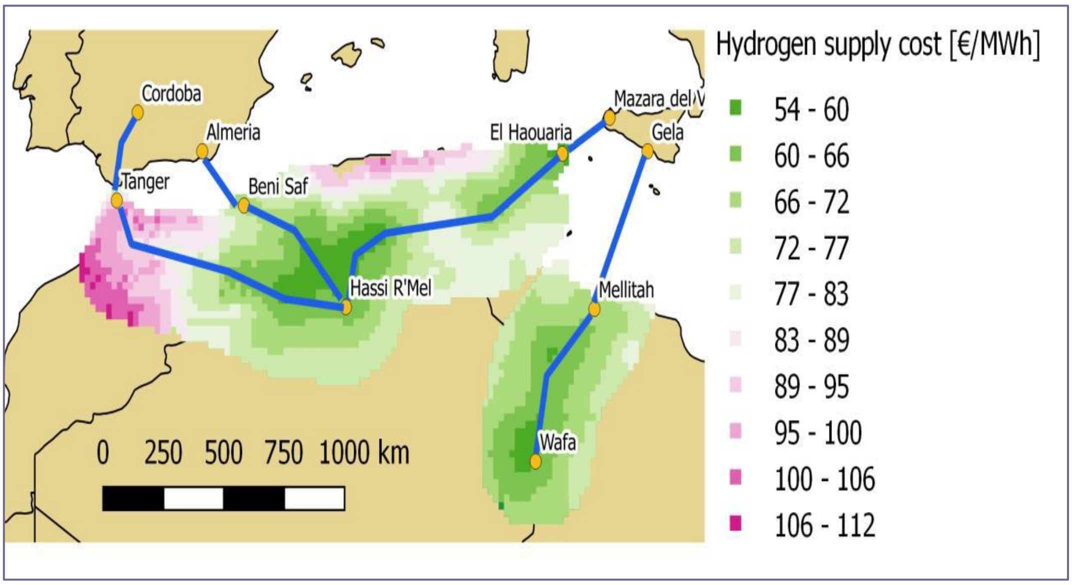
This is summarized in the table below:

Relative weight of CAPEX and energy			
@60€/MWh	**w/o SBSP**	**2*2h/day**	**12 h/day**
CAPEX +M&O ELY	25%	17%	13%
ENERGY	75%	83%	87%
LCOH (€/kg)	4,03	3,65	3,47
ratio energy used	1	1,60	2,27
LCOH @100€/MWh (€/kg)	6,04	5,66	5,48

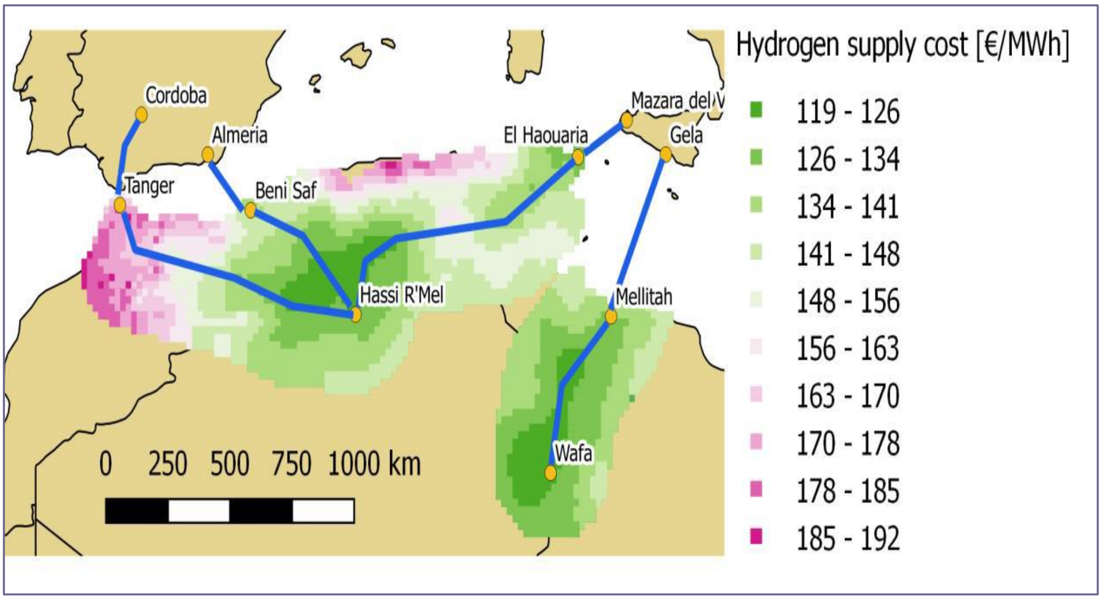
Should the energy cost be at 100 €/MWh, the LCOH of the baseline would jump to 6,04€/kg, while that of the low orbit configuration would go to 5,66€/kg and that of the GEO configuration to 5,48€/kg.

The higher the energy price, the less important is the effect of using a SBSP, from the point of view of the owner of the electrolyzer. Indeed, the relative weight of the fixed costs then gets smaller, hence lesser interest to increase the duty cycle of the electrolyzer (if the price of energy tends towards the infinity, the relative weight of the fixed costs tends to zero).

These results are coherent with another study (*Hydrogen from renewables: Supply from North Africa to Central Europe as blend in existing pipelines – Potentials and costs*, published in 2019 in Applied Energy, see the link), which shows the LCOH in North Africa in different locations, taking into account the variation of many parameters, thus leading to minimum and maximum cases, as shown below:



Levelized hydrogen supply cost (production and transport) in lower cost case (locations in proximity of North African natural gas pipelines)



Levelized hydrogen supply cost in higher cost case (in proximity of North African natural gas pipelines)

Notice on those maps, LCOH are expressed in €/MWh, since the LHV, Low Heat Value of H2, is 33 MWh/ton. A LCOH at 4,03 €/kg then corresponds to 122 €/MWh and a LCOH at 6,04€/kg corresponds to 183 €/MWh.

Since 4 mta of H2 have to be produced in the H2 South Corridor project described above, its illumination by an SBSP in LEO would therefore save about 1,5 billion € per year and 2,24 b€ per year for a SBSP in GEO, for of price of electricity equal to 60€/MWh. At a first order of magnitude, the savings will be equivalent with a higher price of energy, for the reasons explained above.

Lets keep in mind the site in Algeria is at 31% latitude and would involve a 500 km2 PV farm to be illuminated (25-30 km in diameter). By deriving our results from the Chinese study, we have assumed the size of the electrolyzer was 40 MW. It has to be checked how to extrapolate LCOH to gigaWatt scale systems. Since larger systems have a better efficiency, their resulting LCOH is better, meaning the impact of an SBSP on LCOH will be reduced in percentage (but not in absolute value).

We did not take into account the cost of pipelines nor that of compression. Implicitly, this means we have assumed they will use only repurposed CNG (compressed natural gas) pipelines for carrying H2, with no repurposing cost. The delta cost between CNG and H2 compression has been neglected, as well.

Given the fact this project will connect to all Europe, it shows it is most probably much better to illuminate this site or others in North Africa, rather than illuminating sites in Europe.

It is often said the cost of renewable PV power has dropped down significantly over the past ten years. But this also because PV power does not pay the price of its intermittency. Indeed, as shown in the power curve for the GEO case, the surface area of production curve in the case of GEO satellites over half a day is 2,3 times larger than that of a natural illumination. Should an electrolyser draw its power at a constant pace from the grid 24 hours per day, its production will be 4,6 times higher than with a PV farm without SBSP. This means the relative weight of the CAPEX amortization will be divided by 4,6 to become 5,5% instead of 25%. This will directly reduce the LCOH by 20%.

This exemplifies the fact that using renewable, intermittent energy leads to an under-utilization of ground equipment, which in return leads to high LCOH. Hence, the main outcome of using SBSP systems would be a reduction of this intermittency, and thus an improvement of LCOH.

Important notice :

The cost figures provided are coherent with internal calculations in Air Liquide based on current projects. Nonetheless, Air Liquide's data are confidential and apply to our specific cases. This is the reason why we based our calculations on reknown third party entities and experts found in scientific literature. Given all uncertainties and hypotheses, this report gives trends at the first order of magnitude, but enough to see the potential benefit of using a Space Based Solar Power sys