

Space and Terrestrial Solar Power Sources for large-scale Hydrogen Production – A Comparison

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Abstract: Among the different options to fulfil the electric power need, solar power plants represent one of the most promising options in the long term: solar power as abundant and GHG emission free source, combined with hydrogen as energy carrier has the potential to cover the majority of humanity's energy need.

This paper presents the work done at the Advanced Concepts Team of the European Space Agency, comparing large-scale power generation in space with terrestrial options. A quantitative as well as qualitative assessment is presented. The advantage of the space option, a 24 hour/day continuous high solar irradiance in geostationary orbit, transmitted via microwave or laser to dedicated ground receiving sites, weighted by the space transportation and infrastructure needs and transmission losses, is compared to typical parameters of large-scale ground based solutions at favourable geographic locations. The main trade-off is between the high infrastructure and transportation cost of the space options and the storage and transportation needs of the terrestrial options.

Keywords: Solar Power Satellites, solar hydrogen, space-terrestrial comparison

1. Introduction

Within the next 15 to 20 years a significant portion of the European power plants will reach their definitive end-of-life and will have to be replaced. In some of the most dynamic emerging economies, energy requirements are expected to double and triple within the next 20 years. As a consequence, the discussion about the most appropriate energy system for this 21st century is gaining political and public interest. [1][2][3][4]

At the same time, the general public attributes the increasing frequency of natural disasters more and more to greenhouse-gas (GHG) caused climate changes. Health problems caused by air pollution show the limitations of fossil fuel based traffic increases in metropolitan areas. The increasing energy-import dependence on few supplier regions additionally alerts strategic planners and incites to look for viable, sustainable, affordable and realistic alternatives.[5]

This paper tries to contribute to this debate in showing the potential of solar-based solutions. It covers space as well as terrestrial concepts, focuses on specific European examples before enlarging the scope to global views.

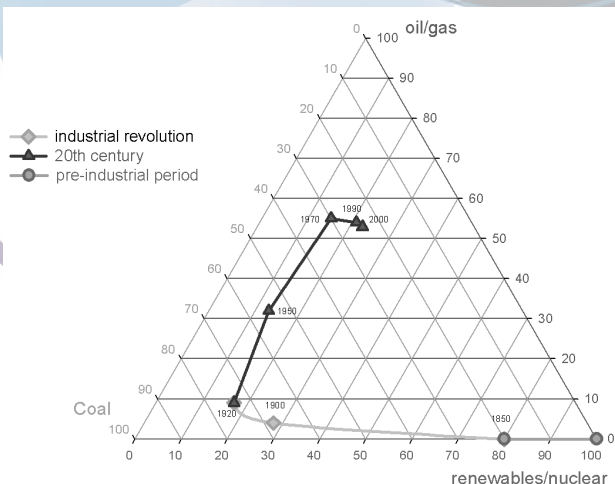


Figure 1: Evolution of humanity's energy sources (values in % of total consumption)

2. Scope of the comparison

Energy Situation 2020

Any attempt to influence the energy choices has to take into account the inherent conservatism of the energy sector, caused by its strategic importance to economic growth and public welfare. However, the globally steady and strong increase of power demand also allows for new sources and energy vectors to appear and gain importance without immediately threatening established energy supply branches. This situation occurred with the introduction of oil and gas at the beginning and the introduction of nuclear energy during the second half of the 19th century.

Plotting the proportional supply share of 1. renewables/nuclear sources, 2. coal and 3. oil and gas as done in Figure 1, shows that this situation occurred at least two times during the 20th century: Since the first world war the share of coal decreased steadily from an all-time high of about 70% to the benefit of oil and gas, the fuel of the transport industry of the 20th century. To a lower extent, the oil crisis of the 70s had a similar effect, when the introduction of nuclear energy led to the levelling of the oil and gas share at about 60%. Currently a trend from oil to gas is observed (not shown in Figure 1), in line with the successive reduction of the carbon content of fuel. (C:H ratio: wood: 10:1, coal: 2:1, oil:1:2, gas:1:4)

Energy vector hydrogen

The introduction of hydrogen as energy vector could lead to another of these turning points and is in line with the steady decrease of the C/H ratio of our fuels. At the same time one observes a separation of energy sources and vectors.

Any future energy system will most probably be a combination of large centralised stations and smaller decentralised power generation units. Furthermore, the dominance of fossil fuel will not decrease significantly within the next 20 to 30 years. On the contrary, most projections foresee an increase and a shift from oil to natural gas.[5]

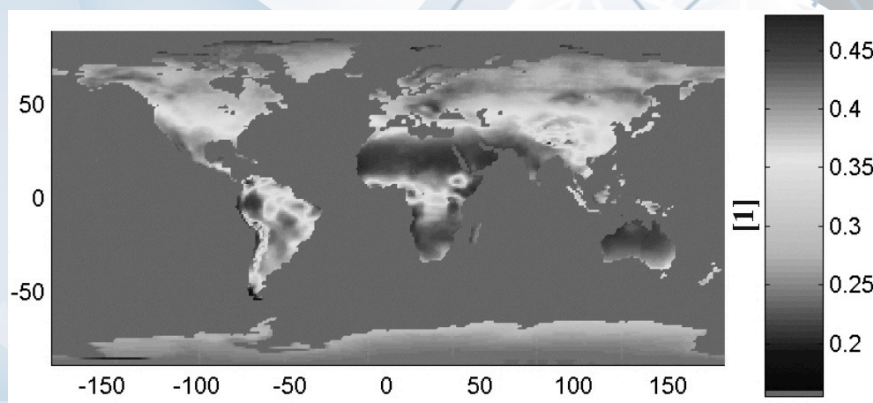


Figure 2: Efficiency of solar thermal troughs.(data: EZMW and NCEP)

Power Levels

Seboldt et al. designed the fully deployed system of the European Solar Sail Tower SPS concept to deliver 513 GWe.[7] This corresponds to the consumption of Europe in 2020, equal to 3/4 of the additional generation capacity foreseen to be installed between 2000 and 2030, requiring a cumulative European investment of 531 B€. [5][6] Each sail tower individually contributing 275 MWe, 18 sail towers transmit to one 5 GWe receiving antenna. The present comparison will consider plant sizes of 550, 80, 5 GWe.

Electricity Load Profiles

Typical European January and July days were taken as reference for solar irradiation data and electricity load needs. Reference January (17 Jan 01) and July (18 Jul 01) load levels were calculated based on data provided by the UCTE network, covering all European countries except Scandinavia.[8] Peak levels for these days were 330 and 280 GWe respectively. For the prospected load levels in 2020, load profiles are assumed to remain unchanged, (Figure 3, right y-axis) leading to the predicted maximum load levels of 500 and 430 GW respectively.[5][6]

3. Terrestrial Solar Power Plants

A. Plant Types and Location

Two types of terrestrial solar power plants are studied: 1. Solar thermal (trough plants and solar towers) and 2. Solar photovoltaic plants. With current technology, solar trough plants show the lowest €/Watt rate. Photovoltaic

systems are still significantly more expensive, but offer the highest potential for efficiency increase and cost reduction. As an example, a location in the western Sahara desert (26N, 14E) with an averaged daily solar irradiance of 280 W/m^2 (2455 kW h/a) is considered.

Solar Irradiation Profiles

For the calculation of a typical solar irradiation profile in January and July, the horizontal irradiation data (provided by NASA for each location on the globe [9]) were crossed with the sunrise and sunset data obtained from the Astronomical Department of the US Naval Observatory [10] and the daily data profile as measured by the Kramer Junction SEGS installation in the Mojave desert, California (US) (for solar thermal plants). All values are hourly averages and were corrected to GMT. Figure 3 shows the hourly irradiation data for the chosen location as well as the 2001 European electricity load profiles.

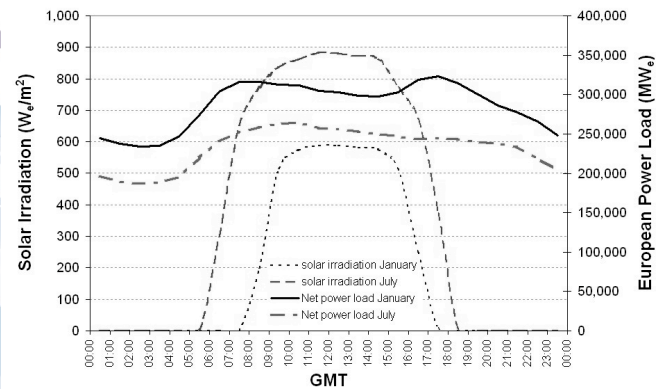


Figure 3: Typical winter and summer day solar irradiation and European electricity load profiles.

Solar Trough Plants

The basic concept of a trough system consists of north-south aligned, one axis sun-tracking parabolic troughs concentrating sunlight about 80 times onto a central absorber pipe in the line of focus, where water is heated up to 400 C . The generated steam drives a turbine before condensing and returning into the cycle. The total *receiver surface* was doubled to account for the necessary land need (*installation surface*).

Current solar thermal power plants in the US and Spain operate with an overall efficiency of 16% [11], result of the 45% efficiency of the parabolic troughs and the 35% efficiency of the steam engine. These are average values, peak values are significantly higher. Projected near-term improvements will lead to 20%.

Solar Tower Plants

The basic principle of solar tower plants consists of a multitude of two-axis movable mirrors (helostats) focussing solar radiation onto a collector atop a solar tower, where usually molten salt is heated (currently at about 575 C) to run a steam generator, in turn driving a turbine.[12]

Solar Photovoltaic Plants

With current technology and at favourable locations, large-scale PV plants are not competitive with solar thermal plants but offer higher improvement capacities in terms of costs and efficiency (lower maturity level).

Contrary to solar thermal conversion, PV based plants don't need the intermediate step of heat production, but generate electricity directly from solar irradiation. They are thus also possible at higher latitudes and lead to a potentially simpler and more effective system.

Hydrogen Production

This study considers only the CO_2 emission free production of H_2 via electrolysis. The technology is well mastered but currently too expensive to be commercially viable to produce H_2 fuel, mainly due to high electricity costs.

Table 1: Selected H₂ properties — H₂ generation.

<i>E</i> need H ₂ O electrolysis	47.7	<i>kWh/kg</i>
prod. Efficiency ¹	70%	
pressurisation (20 MPa)	2.2	<i>kWh/kg</i>
Σ (prod.,pressurisation)	49.9	<i>kWh/kg</i>
total efficiency	67%	
<i>E</i> need for H ₂ O electrolysis	825.9	<i>kWh/m³ (at 20 MPa)</i>

All H₂ energy values are based on the lower heating value of H₂. (Table 1) Water electrolysis and reversible PEM fuel cells are considered. In case of H₂ generation by water electrolysis, high temperature O₂+H₂ driven turbines are studied for the regeneration of electricity.

B. Energy Storage and Transmission

Energy Storage System

Based on a trade-off analysis, underground hydrogen storage was chosen, representing the most cost effective short term hydrogen storage system available. [18] If not calculated in detail (as done e.g. for the hydrogen plant options), the total efficiency of the storage system is assumed to be 60%.

Electrical Power Transmission

In case of electrical power transmission, high voltage direct current lines (HVDC) are assumed, presenting with current technology the lowest €/(*kW km*) ratio. The efficiency of the transmission system is 90%, including line and transformer station losses. With current technology, the maximum per-line load is 5 GWe (taken as basis).

Hydrogen Power Transmission

Instead of delivering energy in form of electricity to European consumer centres, hydrogen could be used as energy carrier either in pipelines, trucks or ships. Only pipeline transportation was considered for this assessment. It is assumed that by 2020 a non-negligible portion of the European energy will be needed in form of hydrogen (e.g. hydrogen trucks, buses and cars, mobile equipment, metropolitan hydrogen grids). Thus the produced hydrogen is considered as “end-product” of the plant.

Currently hydrogen pipelines are operating at 1-10 MPa at flow rates between 310 and 8,900 kg/h. [18][20] For this study, high-pressure pipelines, operating at 20 MPa and a diameter of 0.25 m are considered, assuring a gas flux of 256, 679 kg/sm² or a flow rate of 12.6 t/s. The compressor size is estimated at 45, 000 kW, leading to 2.2 kWh/kg. The 90% pipeline transportation efficiency was derived from data on current natural gas pipelines and might be rather optimistic.² [21]

The pipeline itself functions also as a storage reservoir, containing in its 122,718 m³ 1,330 tons of gaseous hydrogen, representing an energetic value of 159,492 GJ (44,306 MWh). Considering the diameter, the pressure, the lower heating value and the flow rate, the power delivered by one pipeline is 1.5 GW.

Hydrogen Power Generation

There are several ways to regenerate electricity from stored hydrogen. For this assessment, fuel cells with an advanced efficiency of 85% are chosen.

C. Solar Electricity Plants — without storage

In a first approach the plant was designed to deliver energy directly when it is produced, without any local storage capacity. It was investigated whether such plants at ideal locations would be able to cover the European morning and evening peaks and thus reduce the total required generation capacity. For a detailed assessment of the electricity plant options and characteristics we refer to [22] and [23]. The emphasis of this study is on hydrogen plants.

In the case of an 80 GW peak plant (receiver surface covering a square of 21 km side length (442 km²)), the total capacity saving is minimal (no coverage of the evening winter peak demands). In order to reduce the winter generation capacity need by only 1 GW, a receiver surface of 1,000 km² would be required, resulting in a peak power of 190 GW to be transported via the more than 4 times larger HVDC lines as compared to the 80 GW option. It would however not reduce the summer savings (56 instead of 55 GW) but distort the power load profile to be provided by conventional means.

¹ Future levels are expected to be significantly higher. Taking only the electrolyser efficiency, current levels are 75%. [17]

² Current gas pipelines consume about 0.3% of the gas every 150 km to energise the compressors. Theoretically this value could be almost 5 times higher for hydrogen, leading to up to 25% losses over the assumed 2500 km. A more detailed analysis and comparison with existing hydrogen pipeline data is required.

Table 2: 80 GWe plant without storage.

	January	July	
receiver surface ³	442 (884)		km ²
transport capacity	82 (41)		GW
total production	291	773	GW h/day
peak power delivered	39	78	GW
directly delivered	291	773	GW h/day
capacity saving	0.4(0.09%)	54.9(12.8%)	GW

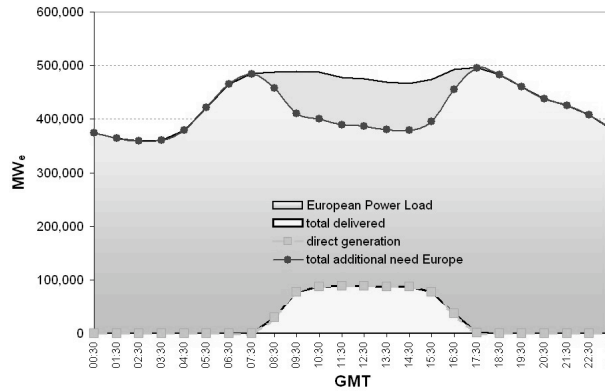


Figure 4: 190 GW plant without storage capacity – winter day.

D. Solar Electricity Plant — with storage

A more detailed assessment of these plant options can be found in [22] and [23]. This section will only summarize the results and refer to the aspects relevant to hydrogen storage and production plants.

In a first approach, the plant was sized to be able to cover the entire European electricity need in 2020. The total receiver surface would cover over 22,000 km², equalling a square of 150 km side length. It would require a minimum H₂ storage volume equal to a sphere of 145 m radius.

Covering 15% of the European electricity need in 2020.

In order to cover about 15% of the projected European need during winter months, a receiver surface of 3,400 km² is required, equalling a square of 58 km side length. With a HVDC line capacity of 82 GW, the plant would cover 17% of the summer load, while still producing an excess of 2,353 GWh/day during the best summer days. The total capacity saving would be 74 GW. Figure 5 shows the resulting winter day load profiles.

The minimal storage need, driven by the winter conditions, is about 1,569 GWh, or 31,500 tons of hydrogen, occupying under the above specified conditions a storage volume equivalent to a sphere of 77 m radius. The summer storage volume need would be much bigger but still largely within normal underground reservoir volumina. Another option could be to use the overcapacity in summer for the production of liquid hydrogen for other applications.

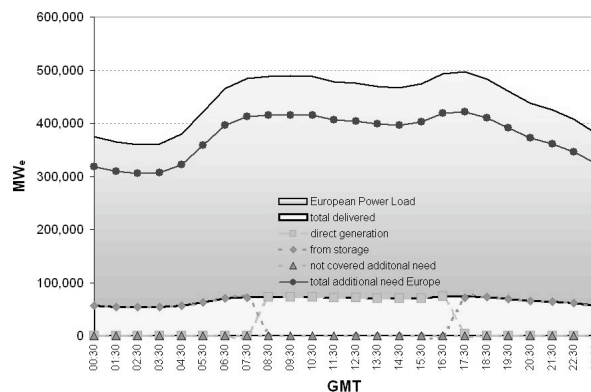
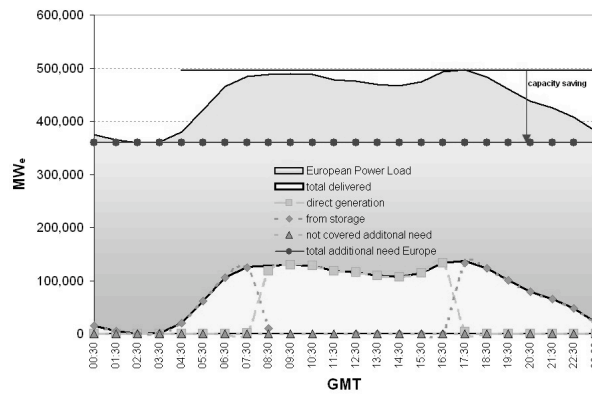


Figure 5: 80 GWe plant - January electric power delivery.

³ installation surface in brackets

Table 3: 80 GWe storage electricity plant.

	January	July	
receiver surface	3,372		km^2
transport capacity	82		GW
total production	2,221	5,898	GWh/day
directly delivered	652	854	GWh/day
into storage	1,569	5,044	GWh/day
stored	941	3,026	GWh/day
over/under-capacity	0	2,353	GWh/day
capacity saving	74	74	GW
H_2 prod. Cap.	226	522	GW
H_2 production	31,433	101,064	t/day
reservoir volume	1,899,379	6,106,879	m^3/day
total water need	282,928	909,671	t/day

**Figure 6: 150 GWe peak load plant — winter day profile.**

The 5 GW plant would need a receiver surface of 225 km^2 , have a minimal H_2 production rate of 302 t/h and a H_2 storage sphere of 31 m radius.

Covering only peak power loads

As a consequence of the large overcapacity requirement due to storage losses a minimal storage option is considered here. The main idea is based on a nuclear/solar energy system combination: the nuclear power plant park supplying constant 359 GW base-load power and the Sahara solar power plant adding the peak load needs. The winter load profile division is shown in Figure 6.

This case is scaled to the winter power demand. A receiver square equivalent of 63 km side length instead of 58 km for the 80 GW plant is needed. Compared to the 80 GW plant, about the same storage capacity is required. However, the total capacity saving is with 127 GW over 70% higher, replacing about 60 large coal plants.⁴

E. Solar Hydrogen Production Plant

The main parameters of a 5 GW hydrogen plant are shown in Table 4. The dimensions of the 4 pipelines offer a total volume large enough for storing the additional daytime energy to permit a continuous H_2 flow. Local storage would only be necessary if the excess production during summer months is not used otherwise (e.g. liquefaction and transport via tankers).

Table 4: 5 GWe hydrogen plant.

	January	July	
receiver surface	225		km^2
transport capacity	5		GW
pipeline number	4		
pipeline reservoir	8,124 / 271		t / GWh
total production	148	393	GWh/day
H_2 total prod.	2,966	7,878	t/day
into storage (pipeline)	2,096	6,738	t/day
H_2 prod. cap.	397	795	t/h
total water need	26,699	70,914	t/day

⁴ The capacity of modern coal plants is assumed to be 2.2 GWe. (e.g. Taichung plant: reported cost of 2.5 B€)

4. Space Solar Power Plants

Space solar power plants were first proposed on an engineering level by Peter Glaser in 1968.[24] The main idea consist in taking advantage of the permanent insolation and no weather or climate effects in outer space (Geostationary orbit in 36,000 km altitude) to transform the solar energy into electricity and transmit it via μ -waves to dedicated receiver sites close to terrestrial consumer centres. Different space solar power plant designs have been proposed in the last 30 years. (e.g.[7][25][26][27]) Most of these designs are based on photovoltaic energy conversion and wireless power transmission via μ -wave at either 2.45 or 5.8 GHz. Table 5 shows the main parameter of the European Sailtower concept.[7][28]

For a review and comparison of recently proposed solar power plants with μ -wave power transmission, it is referred to [27]. The present assessment tries to focus on the principal characteristics of laser based space solar power plants.

Table 5: European Sail Tower Concept characteristics.[32]

Orbit	GEO		
Final Nr. of SPS	1870		
SPS Tower	length	15	km
	mass	2140	mt
	electricity prod.	450	MWe
Twin module	dim.+tether	150x300x350	m
	mass	9	mt
	electricity prod.	7.4	MWe
emitting antenna	400 000	magnetrons	GHz
	mass	1,600	mt
	energy emitted	400	MW
receiving Antenna	final number	103	
	antenna size	11x14	km
	site+safety zone	27x30	km
del. power	per SPS tower	275	MWe

Both are somehow related to the power/mass ratio of photovoltaic cells. During the last years, the worldwide PV market has shown an unprecedented increase of 32% from 1990 (16 GWh) to 2001 (339 GWh).[29]

Space solar power plants transmitting power via laser would be able to take advantage from already existing terrestrial installations: land surfaces, receivers, power management systems and power transmission lines to consumer centres. To a certain but lower extent the same is valid for SPS transmitting via μ -waves, since it seems possible to either integrate rectennas into the PV surfaces or use them as two layers since the rectenna installation would probably not produce much shadow.

Laser concepts are often discarded in SPS studies since many subcomponents are on a quite low technology readiness level.[30] However, laser research is realising important progress and some spin-offs from intense defence related research can be expected within the time frame under consideration. For a more detailed study on laser based SPS systems in combination with terrestrial plants we refer to [22] and [23].

5. Economic Comparison

A. Cost factors for terrestrial solar power plants

To the knowledge of the authors, nine solar thermal power plants have been installed worldwide, covering a total surface of about 7 km² and delivering around 800 GWh/a. The first plant, installed 1984 in the Mojave Desert in California produced at 0.27 \$/kWh while the ones installed in 1991 managed to produce at rates as low as 0.12 \$/kWh.[32] For a plant size of 500 GW, economies of scale would also apply, not taken into consideration here if not specially mentioned. All main cost estimations are summarised in Table 6.⁵

Solar Plants

Solar Trough Plant — electricity production

Current values for the cost of large-scale solar trough plants are in the order to 215 €/m². Technological advances and economies of scale are expected to reduce this value to 107 €/m². The cost for the thermal plant, generating electricity with proven thermodynamic technology is estimated 850 €/kWe.

⁵ Land costs for the plants are not considered. All values are converted into € under the assumption of 1€=1US\$.

Solar PV plant

Only very few mid-scale photovoltaic electricity plants are operating and most of the data were obtained from study assessments.⁶ Due to the fixed installation and the absence of moving parts, the existing plants show very low maintenance and operations costs, typically lower than 1% of the total project costs.⁷ The main reason for the uncompetitive high-end price of electricity produced by PV cell plants is the high production cost of PV cells, the single most important cost factor.

Today the cost of single-crystal and polychrystalline silicon modules is about 4 €/Wp, including all costs as well as marketing and management overheads. It has to be noted that the silicon module prizes have been essentially stable between 3.75 and 4.14 €/Wp for nearly 10 years while manufacturing costs have dropped by over 50%. It seems therefore likely that even current full load manufacturing costs for single-crystal silicon modules could be in the order of 1.4 €/Wp.

Most of the worldwide research effort is now on thin-film photovoltaic cells. Together with concentrators, these are expected to allow profitable resell prices in the range of 1.25 €/W within the next 10 years.

For the financial assessments of this report PV module prizes of 2 (cons.) and 1 (adv.) €/Wp are taken as basis.

Hydrogen generation

For this assessment, hydrogen is produced via water electrolysis with a proton exchange membrane (PEM) electrolyser. Maddy et al.[40] quote an expected PEM fuel cell installation cost of 1,621 and 333 €/kW in 2005 and 2020 respectively. These values are taken as the conservative and advanced references for the present assessment. The (on-site supplied) electric energy is not accounted for in terms of financial cost. Miller et al. report that *Stuart Energy Systems* expects even lower installation costs of 170 €/kW for large-scale electrolytic hydrogen plants.[35]

For the chosen high-pressure system, the cost of the compressors (20 MPa) is non-negligible. The investment costs are estimated at 800 (adv.) and 650 (cons.) €/kW.[36] Their operating costs have been estimated at 2.2 kW h/kg.

Energy Transportation

HVDC lines: The current cost of HVDC power transmission lines is about 70 €/(kWe 1000 km) for land lines and 716 €/(kWe 1000 km) for sea lines. The cost for the HVDC stations amounts to 60 €/kWe per station. For the optimistic assessment (advanced), a 20% reduction of these values until 2020 is assumed based on economics of scale and technology improvements.

Table 6: Cost estimates.

Plant	cons.	adv.	
trough surface	215	107	€/m ²
thermal plant (trough)	850	850	€/kWe
PV surface	2	1	€/Wp
PV surface	294	150	€/m ²
Transportation			
HVDC land line	70	56	€/(kWe · 10 ³ km)
HVDC sea line	716	572.8	€/(kWe · 10 ³ km)
HVDC stations	60	48	€/kWe
H ₂ pipeline (0.25 m)	154	103	€/(kWh ₂ · 10 ³ km)
H₂ Production and Storage			
H ₂ prod. (PEM)	1,621	333	€/kW

Hydrogen pipelines: While there are reliable numbers available for high voltage long distance power lines, published data on long distance hydrogen pipelines are only estimations. Several authors have estimated hydrogen pipelines costs.[14][16][18][37] Some data are pure estimates without specifications on the diameter. The most reliable data were the ones derived from existing gas pipelines (dependent on the diameter).[21]

Veziroglu et al. estimate that the cost of hydrogen pipelines would be 50% to 80% higher than that of a natural gas pipelines.[16] True evaluates the cost of a 100 cm gas pipeline at 62,000 €/km.[21] Extrapolation of this value to the proposed diameter (250 cm), including additional costs as calculated by Veziroglu et al. leads to a total cost of about 233,000 €/km, equivalent to 154 €/(kWh₂ 1000 km). These values are taken for the conservative estimates,

⁶ The most powerful PV grid electricity plants being in the order to some hundreds of kW (e.g. in Sacramento (US))[33]

⁷ For three reference projects (Solarex Residential (329 kW), Solarport at Sacramento Airport (128 kW), Rancho Seco PV-3 System (214 kW)) the operations and maintenance costs range between 0.25 and 0.68% of the total project costs.

while the *advanced* values estimate the cost of hydrogen pipelines in 2020 equal to the one for existing gas pipelines, 103 €/(kWH_2 1000 km).⁸

Energy Storage

Only underground hydrogen storage was taken into consideration. Wurster et al. estimate the cost of underground storage at about 3-8 €/kg.[36][38]

Plant Costs

Based on the above assumptions and the technical choices described, Table 7 list the resulting total costs for all the considered options. The receivers and the fuel cells represent the most important cost factors for the PV and trough options. The cost estimates in Table 7 include approximate capital costs of 20% of the total installation costs.

B. Cost factors for space solar power plants

Estimations of the costs involved in the development and operations of space solar power plants are subject to high uncertainties. In this assessment, the most recent comprehensive studies performed in Europe and the US were taken as basis.

European Sailtower Costs

Klimke estimates the total development costs for the European solar tower at 265 B€, more than double the development costs estimated by NASA's reference study.[28][39] The development costs include the development of a heavy lift launch vehicle (20 B€, a probably rather optimistic estimation). The individual production costs per solar tower is with 1.24 B€ comparably low. The transportation into the final GEO orbit adds about another 1 B€ per sail tower. The ground segment is estimated at about 7 B€ not including land costs (18 B€ with land costs at 20 €/m²) per 5 GWe rectenna (120 km², circle of 6 km radius), but inclusive of capital costs (4% p.a.).

Table 7: Cost estimates of terrestrial plant options. (all values in B€; incl. capital costs)

		PV			
		trough		trough	
		cons.	adv.	cons.	adv.
500 GW plant					
without storage		1,240	661	1,122	721
with storage	min	11,867	5,223	10,965	5,681
	max	15,756	6,052	14,854	6,510
H_2 plant	min	12,692	5,399	11,791	5,857
	max	16,427	6,193	15,525	6,651
80 GW plant					
without storage		186	99	168	108
with storage	min	1,780	784	1,645	852
	max	2,363	908	2,228	976
H_2 plant	min	1,904	810	1,769	879
	max	2,465	929	2,329	998
5 GW plant					
without storage		12	7	11	7
with storage	min	119	52	109	57
	max	157	60	148	65
H_2 plant	min	127	54	118	59
	max	165	62	156	67

Table 8 summarises the cost estimates for the European Sail Tower concept.[7] Including the development and operations efforts, the 5 GWe option amounts to 334.6 B€, higher than the comparable terrestrial plant (Table 7). The 80 GWe option amounts to 1,386 B€, lower than the conservative but higher than the optimistic terrestrial plant (including H_2 storage) (Table 7). The larger the plant gets, the more favourable the space option. For the 500 GWe plant covering the entire European need in 2020, the space option is only 57% of the conservative estimation for terrestrial PV plants, and only 35% higher than the optimistic one.

⁸ While this number is significantly higher than the one for electricity transportation, several authors claim that over long distances, energy transportation in form of hydrogen is cheaper than in form of electricity.[14][34]

Table 8: European Sail Tower Concept cost estimates.

development incl. LV	265	B€
1 sail tower ⁹ production	1.24	B€
(275 MWe) E2O transp.	0.92	B€
oper.&maint.	0.044	B€/a
total	3.48	B€
18 sail towers production	22.3	B€
(5 GWe) E2O transp.	16.6	B€
oper.&maint.	0.8	B€/a
total	62.6	B€
290 sail towers production	360	B€
(80 GWe) total.	1,009	B€
1818 sail towers production	2,254	B€
(500 GWe) total.	6,327	B€
Ground element ¹⁰		
rectenna (≤ 5 GW)	7(18)	B€
rectennas (80 GW)	112(288)	B€
rectennas (500 GW)	700(1800)	B€

Land Costs

The above comparison does not include eventual land costs for the terrestrial power transmission lines for both options. These could potentially alter the comparison in favour of the space option, since receiver sites could be much closer to consumer centres: Modern 5 GW electrical lines require about 50-60 m corridors. With land costs at 20 €/m², 3.5, 56 and 385 B€ would have to be added to the terrestrial 5, 80 and 550 GW options respectively. No data on hydrogen pipeline land requirements could be obtained, but in principle these should be much smaller. With estimated 10 m corridors, the land costs would be 0.5, 8 and 55 B€.

6. Space and Terrestrial Plants – Conclusions

Conclusions

The analysis has shown that the considered terrestrial solar power plants without storage facilities are not able to reduce the electricity generation capacity need of Europe, essentially due to the late evening consumption peak in winter months. To overcome this deficiency and be able to deliver electricity on-demand, on-site energy storage systems need to be included, increasing the total investment by almost a factor 10. (Table 7) Hydrogen storage systems are the evident solutions to this problem. Since hydrogen would most probably thus be required in any case, this study assesses the possibility to directly use space solar power concepts to produce hydrogen on a large scale, enhancing the foreseen trend of the gradual introduction of hydrogen as energy vector.

SPS concepts suffer from upfront investment needs and low total W/kg ratios. They profit from terrestrial solar power plant technology developments and sharing of ground infrastructure. Space option system costs are comparable to ground system costs. The following paragraphs show first results of an ongoing work at ESA's Advanced Concepts Team optimising combined space/terrestrial solar plant systems. Cost regions deduced from Table 7 are approx. 50-100 B€ and 700-1,600 B€ for 5 GW and 80 GW plants.

Outlook

GEO space solar power plants have nearly continuous irradiation by the sun. Dependent on the LEO/MEO orbit altitude, exposure/eclipse ratios are still much higher than for most locations on Earth.

First, a suitable orbit had to be found that would allow the passage over a Sahara-based plant during time-periods when this one would not be able to satisfy the demand (winter evening peaks). This means automatically lower orbits than GEO, implying shorter transmission distances and the necessity of enhanced steering and attitude & orbit control.

Non-GEO SPS serving only one ground station would be somehow "unproductive". Since winter evening peak demands are the main concern, a second station with about 12h time difference is considered. The Chinese/Mongolian Gobi desert offers a location suitable for a terrestrial solar plant to be enhanced by an SPS serving the Sahara based plant. The Gobi desert is located at 40N and 112E. Such a plant would be able to serve the fast growing Chinese as well as the Japanese electricity/hydrogen market. With 1,700 kWh/m, the solar irradiation conditions are not as good as in the Sahara, but big consumer centres are relatively close and local population density is low.

⁹ lifetime estimation: 30 years

¹⁰ Power distribution lines not included values in brackets include land cost estimates

Orbits

In order to assure long power transmission times, three different solutions are envisaged:

Option 1 sun-synchronous repeating Molniya orbit;

Option 2 high elliptic nearly sun-synchronous Molniya orbit with a 1 year phase drift;

Option 3 high repeating circular orbit.

For more detailed orbital information on the three option it is referred to [22] and [23].

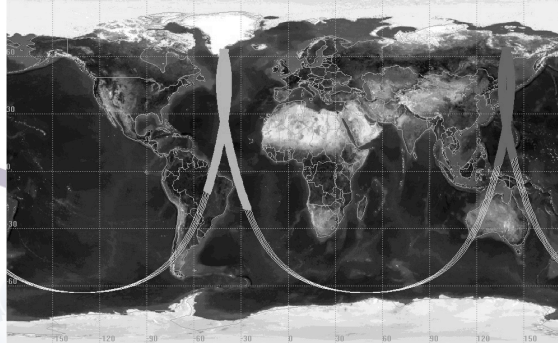


Figure 7: Option 2

high elliptic nearly sun-synchronous Molniya orbit

The second option is a high elliptic orbit, with an apogee higher than GEO at 39,955 km and a comparably low perigee at 500 km. The space solar power plant stays most of the orbital time over the northern hemisphere. January ground tracks are shown in Figure 7. The effect of the high eccentricity to the gravity gradient stabilised SPS requires some additional analysis.

As shown in Table 9, both plants are accessed during the (local) evening peak times in winter months. During summer, the space power plant is covering almost the entire day until the late afternoon in Europe and the second half of the local night in eastern Asia including the morning peak.

As indicated in Table 9, the ground track of the satellite is only *close* to be sun-synchronous, thus slowly drifting eastwards. The drift speed was chosen in order to allow for a 1-year phase repetition, leading to evening peak coverage in winter months and morning to mid-afternoon coverage during summer months.

Table 9: Option 2: Sahara and Gobi plant; access times.

	Sahara Plant	Gobi Plant
	start-end / duration (GMT) / hours	start-end / duration (local time) / hours
January	18:16-05:34 / 11.3	13:22-00:23 / 11.0
April	05:38-16:27 / 10.8	13:01-23:11 / 10.2
July	20:11-01:38 / 5.5	
October	04:40-15:56 / 11.3	23:43-10:39 / 10.9
	06:24-11:51 / 5.4	23:15-09:19 / 10.1
	15:49-02:40 / 10.9	

Space plant choices – ongoing work

In case of a combination of a 5 GW space plant using microwave power transmission at 2.45 GHz with a terrestrial 5 GW plant, the rectenna surface would need to be about twice the terrestrial plant installation surface. Taking into account the probable different shapes (rectangular versus elliptic), a 5 GW plant would best integrate with a 15 GW terrestrial plant.

In case of a combination of terrestrial PV plants with space plants transmitting via laser, the actual orbital position dependent power transmission rates have to be assessed as a function of the fixed tilt angles of the terrestrial PV panels. An optimisation process needs to be run, taking into account the geographical location, the associated solar angles and the orbit of the solar power plant(s).

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