

Space and Ground Based Large Scale Solar Power Plants A European Perspective

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The paper presents a comparison of terrestrial large-scale solar power plant solutions with space-based solutions. The comparison is made in terms of total cost, cost/kWh as well as technology requirements and risk in a timescale reaching from state-of-the-art technology to foreseeable technological advances within approximately 25 years. The application focus of the paper is on the larger continental European situation.

I. 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. 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 caused climate changes. Health problems caused by air pollution show the limitations of fossil fuel based traffic increases in metropolitan areas. The increasing European 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 — space as well as terrestrial ones — for the long-term, larger European energy context. The scope of the considerations is on the wider European context, worldwide solutions being compared by Seboldt et al.[6].*

II. 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.

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. Electricity production is increasing over-proportionally and the introduction of hydrogen will have a similar effect.

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, 7] For this study, a dominantly fossil fuel based economy with a small but increasing hydrogen energy system is assumed (2020).

The comparison of terrestrial and space solar power plants is limited to large plants capable of providing significant portions of the European electricity need.

Power Levels Seboldt et al. designed the fully deployed system of the European Solar Sail Tower SPS concept to deliver 513 GW_e [8]. 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, 7] The present comparison will consider plant sizes of 550, 80, 5 GW_e .

European Electricity Load Profiles Typical January and July days were taken as reference for solar irradiation data and European 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. Peak levels for these days were 330 and 280 GW_e respectively. For the prospected load levels in 2020, load *profiles* are assumed to remain unchanged.(Fig. 1, right y-axis)

III. 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. A location in the western Sahara desert(26°N, 14°E) with an averaged daily solar irradiance of 280 W/m^2 (2,455 kWh/a) is considered.

* In addition to the difference of European and global solutions, this paper tries to focus on laser concepts and the integration of solar plants into a hydrogen economy versus a focus on μ -wave WPT in the paper by Seboldt.[6]

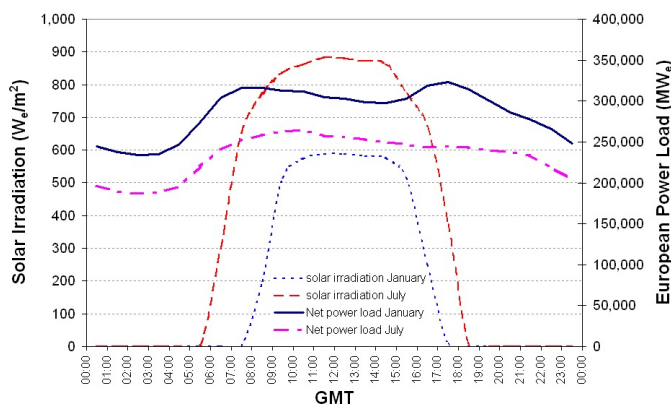


FIG. 1: Typical winter and summer day solar irradiation and European electricity load profiles.

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. Fig. 1 shows the hourly irradiation data for the chosen location as well as the 2001 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 $\sim 16\%$ [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 (heliostats) focussing solar radiation onto a collector atop a solar tower (concentration ratios in the order of 500 to 1000), where usually molten salt is heated (currently at about 575°C) to run a steam generator which is driving a turbine. Solar tower sizes are currently designed

for power levels in the order to 200 MW_e.^[12]

Solar thermal plants usually need considerable amounts of water for their cooling systems. These are not taken into account in this assessment. Alternatives like dry cooling are more expensive. In the case of the Gobi-plant (Section VI) these might be necessary.

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 plants, PV plants are capable of using direct as well as indirect solar irradiation and become advantageous over solar thermal plants at higher latitudes. Most plant concepts consider fixed mounted PV arrays with tilt angles between 10 and 40° , depending on the geographical location.

The overall efficiency of the PV system was assumed to be equal to the one for solar trough plants for the size of the receiver area. For the level of detail necessary for the present study, the following size values for electricity plants are thus applicable to solar thermal as well as PV plants. For a more thorough investigation, calculations on hourly global irradiance conditions depending on the receiver inclination and the location on Earth are required as proposed in a simplified model by Olmo et al.[13].

Due to the fixed receiver surfaces, the spacing between PV panels can be much smaller than for the sun-tracking solar troughs, making the actual *installation surface* only slightly larger than the *receiver surface*.[§]

Hydrogen Production Currently, several available technologies (e.g. reforming, gasification, electrolysis) are used to produce hydrogen from a variety of feedstocks (e.g. natural gas, biomass, water). Steam methane reforming is the most common and least expensive one, delivering on an economic industrial basis almost half of the worldwide produced hydrogen.[14, 15, 16]

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.

All H_2 energy values are based on the lower heating value of H_2 . (Tab. I) Water electrolysis and reversible PEM fuel cells are considered. In case of H_2 generation by water electrolysis, high temperature $\text{O}_2 + \text{H}_2$ driven turbines are studied for the re-generation of electricity. Possible synergies with the turbine system of the solar thermal plant need further investigation. The trade-off between electrolyser and $\text{O}_2 + \text{H}_2$ driven turbines and completely reversible PEM fuel cell systems still needs to be done.[¶]

[†] Some plants have additional gas firing capabilities, increasing the per day system efficiency and economic viability of the plant. For the present assessment, this option is not included.

[‡] Efficiencies vary between summer and winter irradiation conditions. These variations were accounted for in the present assessments.

[§] Since land costs are not taken into account and power distribution and management costs are averaged, this difference has no influence on the presented comparison.

[¶] Advanced production methods based on photobiological processes

TABLE I: Selected H_2 properties.

	LHV	HHV	
Energy density	119.96	141.79	MJ/kg
	33.32	39.39	kWh/kg
H_2 density @101.2kPa	0.0838		kg/m^3
Energy density	10.06	11.89	MJ/m^3
	2.79	3.30	kWh/m^3
H_2 density @20MPa	16.5493		kg/m^3
Energy density	1,985.25	2,346.52	MJ/m^3
	551.46	651.81	kWh/m^3

TABLE II: Selected H_2 properties — H_2 generation.

E need H_2O electrolysis	47.7	kWh/kg
prod. efficiency ^a	70%	
pressurisation (20 MPa)	2.2	kWh/kg
Σ (prod.,pressurisation)	49.9	kWh/kg
total efficiency	67%	
E need for H_2O electrolysis	825.9	kWh/m^3 (at 20 MPa)

^aFuture levels are expected to be significantly higher. Taking only the electrolyser efficiency, current levels are $\geq 75\%$. [18]

B. Energy Storage and Transmission

Energy Storage System Based on a tradeoff analysis, underground hydrogen storage was chosen, representing the most cost effective short term hydrogen storage system available. [19] The technique consists of pumping gaseous hydrogen into underground caverns or porous rock areas with an impermeable caprock above (e.g. a porous layer saturated with water). Salt mine caverns, depleted gas wells and mined caverns are possible. [20]** 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 $\text{€}/(kW km)$ ratio. The efficiency of the transmission system is 90%, including line and transformer station losses. With current technology, the maximum per-line load is $5 GW_e$ (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. Due to the amount of hydrogen under consideration, the low volumetric energy density of gaseous hydrogen and the high energy requirements of liquefaction 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

(algae, bacteria) might well prove higher overall efficiencies than the presented systems but the maturity of the systems does not yet allow these technologies to be considered in this study. [17]

** Cushion gas, that occupies the storage volume at the end of the discharge cycle is not considered in this study.

TABLE III: H_2 pipeline properties at 20 MPa.

flow rate	12.6	kg/s
	1.51	GW
length	2,500	km
diameter	0.25	m
volume	122,718	m^3
H_2 mass	2,031	$tons$

(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 . [19, 21]^{††} 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 $kg/s \cdot m^2$ or a flow rate of 12.6 t/s . The compressor size is estimated at 45,000 kW , leading to 2.2 kWh/kg . (Tab. III) The 90% pipeline transportation efficiency was derived from data on current natural gas pipelines and might be rather optimistic.^{‡‡} [22]

The pipeline itself functions also as a storage reservoir, containing in its 122,718 m^3 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 re-generate electricity from stored hydrogen. For this assessment, fuel cells with an advanced efficiency of 85% are chosen. An alternative to be investigated would be an oxygen/hydrogen steam generator as developed by DLR, that might be able to use the same thermal installations as the thermal plant of solar trough installations by adding water to cool the combustion temperature. [16]

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.^{§§}

In the case of an 80 GW peak plant (receiver surface covering a square of 21 km side length (442 km^2)), the total capacity saving is minimal. Despite the generation of almost 300 GWh/day in winter and 800 GWh/day in

^{††} e.g. Since 1966 Air Liquide operates pipelines in France and Belgium of a length of 290 km and pressure levels of 6.5-10 MPa

^{‡‡} 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.

^{§§} For a detailed assessment of the electricity plant options and characteristics we refer to [6] and [23]. Strickland published an extensive study on a base-load plant comparison in [27]. The emphasis of this study is on hydrogen plants.

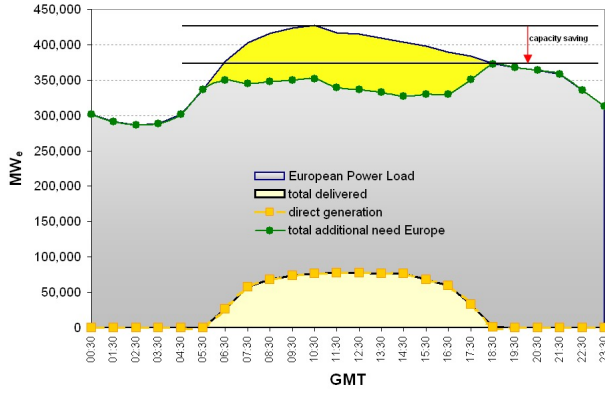


FIG. 2: 80 GW plant without storage capacity - summer day.

summer, the winter capacity saving is not even half a GW , the equivalent of a standard modern gas plant. The summer capacity saving would be significant, mainly due to the missing evening peak: $55 GW$. The resulting daily summer load profile is shown in Fig. 2.

In order to reduce the winter generation capacity need by only $1 GW$ a receiver surface of $1,000 km^2$ would be required, resulting in a peak power of $190 GW$. The HVDC lines would be more than 4 times larger 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.

This demonstrates that, despite the location about 2 hours west of central European consumer centres, such a power plant would not be able to cover the European winter evening peak and would thus not reduce the required total generation capacity (amount of conventional plants). It would however be able to sell most of the produced electricity at high (peak) price levels.

In a next step, local storage capacities are included.

D. Solar Electricity Plant — with storage

Covering the entire European electricity need

In a first approach, the plant was sized to be able to cover the entire European electricity need in 2020. It is necessary to over-dimension the plant to take into account storage needs and losses.

Since the electricity need in winter is higher and solar irradiation lower, winter months have to be taken as base-line, accepting an overproduction during summer months.

The total receiver surface would cover over $25,000 km^2$, equalling a square of $159 km$ side length. It would require a minimum H_2 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 $3,400 km^2$ 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 $74 GW$. The

TABLE IV: $150 GW_e$ peak-load electricity plant.

	January	July	
receiver surface	3,963		km^2
transport capacity	151		GW
total production	2,609	6,931	GWh/day
directly delivered	1,080	1,464	GWh/day
into storage	1,529	5,467	GWh/day
stored	918	3,280	GWh/day
over/under-capacity	0	2,746	GWh/day
capacity saving	137	127	GW
H_2 prod. cap.	236	582	GW
H_2 prod. rate	4,725	11,668	t/h
H_2 production	30,644	109,543	t/day
reservoir volume	1,851,658	6,619,215	m^3/day
equiv. sphere rad.	76	116	m
total water need	275,820	985,987	t/day

general parameters of the plant are similar to the ones in Tab. V.

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.

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 — also shown in section V — 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 Fig. 3.

This case is scaled to the winter power demand. The dimensions of the plant are given in Tab. IV. 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.^{***}

E. Solar Hydrogen Production Plant

The main parameters of a hydrogen plant to supply 15% of the European energy vector need in 2020 are shown in

^{¶¶} About 250 modern large nuclear power plants would be necessary (e.g. French Civeaux plant with $1.45 GW$). Alternatively, adding the foreseen hydroelectric and wind capacity in 2020, $95 GW$ and $57 GW$ respectively, “only” 142 nuclear plants would be required.[7]

^{***} The capacity of modern coal plants is assumed to be $2.2 GW_e$ (e.g. Taichung plant with a reported cost of $2.5 B€$)

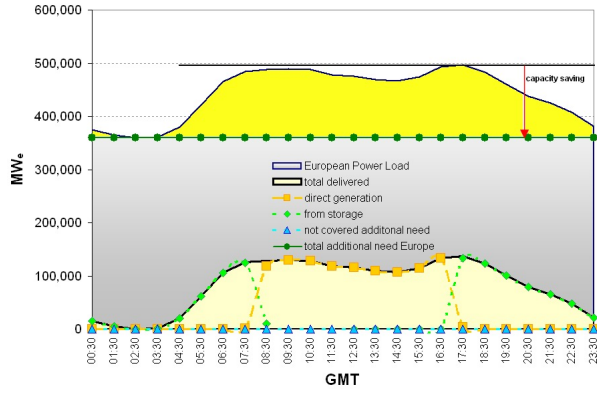


FIG. 3: 150 GW_e peak load plant — winter day profile.

TABLE V: 80 GW_e hydrogen plant.

	January	July	
receiver surface	3,372		km^2
transport capacity	82		GW
pipeline number	55		
H_2 transport cap.	693		kg/s
pipeline reservoir	111,700		t
	3,722		GW_h
total production	2,221	5,898	GW_h/day
H_2 total prod.	44,494	118,177	t/day
directly delivered	13,061	17,113	t/day
into storage (pipeline)	31,433	94,586	t/day
into storage (reservoir)	0	6,478	t/day
H_2 prod. cap.	5,959	11,919	t/h
reservoir volume	0	391,432	m^3
equiv. sphere rad.	0	45	m
total water need	400,490	1,063,704	t/day

Tab. V. The dimensions of the 53 pipelines offer a total volume large enough for storing the additional daytime energy to permit a continuous H_2 flow able to serve about 20% of the European electricity-equivalent need in 2020. Local storage would only be necessary if the excess production during summer months is not used otherwise (e.g. liquification and transport via tankers).

The dimensions of the 5 GW plant would be equal to the electricity delivery plant, without local storage reservoirs since the 4 pipelines would be able to contain all the excess H_2 produced. The minimal H_2 production rate would be slightly higher with 397 t/h .

IV. SPACE SOLAR POWER PLANTS

Different space solar power plant designs have been proposed in the last 30 years. (e.g.[8, 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 . Tab. VI shows the main parameter of the European Sailtower concept.[8, 28]

For a review and comparison of recently proposed solar power plants with μ -wave power transmission, we refer to the Peter Glaser lecture 2003.[6] The present assessment tries to focus on the principal characteristics of laser based space solar power plants.

TABLE VI: European Sail Tower Concept characteristics.[28]

Orbit	GEO		
Final Nr. of SPS	1870		
SPS Tower	length	15	km
	mass	2140	mt
	electricity prod.	450	MW_e
Twin module	dim.+tether	150x300x350	m
	mass	9	mt
	electricity prod.	7.4	MW_e
emitting antenna	400 000 magnetrons		
	frequency	2.45	GHz
	radius	510	m
	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	MW_e

There are some dominant reasons, why solar power satellites are still not close to realisation despite the several times renewed conclusion: technical feasibility, ecological cleanness as well as long-term economical viability. Prohibitive launch costs, limited launcher capacities, enormous masses and large upfront investments are certainly among the most prominent reasons.

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 GW_h) to 2001 (339 GW_h).[29] The installed capacity within the EU grew even at a rate of 37.7% in 2002,[30] but the total energy produced is still extremely low.[31]

Independent of the choice of the transmission technology, a strong and continuous increase of terrestrial PV utilisation, leading to large scale centralised solar power stations at favourable locations is probably necessary in order to increase the power/mass ratio, the efficiency and the power/cost ratio to levels enabling space solar power plants. Space solar power plants thus can only benefit from an early and strong terrestrial PV market.

Space solar power plants transmitting power via laser would then 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-based concepts Laser concepts are often discarded in SPS studies since many subcomponents are on a quite low technology readiness level.[32] However, laser research is realising important progress and some spin-offs from intense defense related research can be expected within the time frame under consideration.

One of the biggest deficiencies of laser power transmission is the low laser generation efficiency, requiring very large light collecting and radiator surfaces.

For a first approach to orders of magnitude of a possible laser space solar power satellite, the *SPARK*-model was used.[32] Many of the involved technologies are in an early development phase and results are somehow speculative.

A GEO laser based system, using PV arrays (GaInP/GaAs/Ge with concentrators operating at 32% efficiency and a mass of 1.6 kg/m^2), advanced GaAs laser diodes emitting at $840 - 890 \text{ nm}$ with an assumed 70% generation efficiency and only 0.02 kg/W lead to an approximate satellite mass of 384,000 tons to deliver 5 GW_e onto a ground based PV receiver system. This configuration, although optimistic, would still be about 6 times more massive than the 5 GW Sailtower option using μ -wave power transmission. Important progress remains to be done in laser generation specific mass kg/kW and efficiency in order to profit from its advantages.

Laser beam steering In addition, electronic laser steering would probably be required to keep the mechanical complexity and mass within acceptable levels. Currently some control over the phase of laser diode arrays is reported.* While this might not directly lead to phase controlled, steerable laser beams, one can consider it as a first step. The strong military interest in these technologies allow to expect considerable defense motivated spending and, in a second phase, technology spin-ins into the SPS concepts.

Space Mirrors Another approach is the reduction of the space segment to its absolute minimum necessary for the augmentation of terrestrial solar power plants: Orbiting mirrors might be an option. The basic motivation is the relative simplicity of such systems compared to standard SPS concepts: instead of transforming incoming solar irradiation into “transmittable” energy forms and losing at each conversion step, it deviates the energy stream in form of light to ground-based facilities that are already existing to convert regular solar energy into electricity. Simple optics quickly show with flat mirrors reasonable ground spot energy densities require very low altitudes, thus low access times. Focussing mirrors need additional optics to steer the collimated beam, leading to additional spectral diffraction issues, losses and complexity. These have to be trades against classical system properties.

New technology developments in mirror design and control are however promising. Considerations are based on the Russian *Znamya* experiments carried out during the 1990s and the plants for the *SolarKraft* (area of $31,000 \text{ m}^2$; 0.016 kg/m^2). Large focussing mirrors with probably some sort of adaptive optics† show the potential to dramatically decrease the kg/m^2 ratio. Inflatables and rotation stabilised structures are an option.

V. 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 km^2 and delivering around 800 GWh/a . The first plant, installed 1984 in the Mojave Desert in California produced at $0.27 \text{ \$/kWh}$ while the ones installed in 1991 managed to produce at rates as low as $0.12 \text{ \$/kWh}$. [34] 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 Tab. VII.‡

1. Solar Plants

Solar Trough Plant — electricity production

Current values for the cost of large scale solar trough plants are in the order to 215 €/m^2 . Technological advances and economies of scale are expected to reduce this value to 107 €/m^2 . The cost for the thermal plant, generating electricity with proven thermodynamic technology is estimated 850 €/kW_e .

Solar PV plant Only very few mid-scale photovoltaic electricity plants are operating and most of the data were obtained from study assessments.§

Due to the fixed installation (no sun tracking, see subsection III A) 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.¶

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 €/W_p , 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 €/W_p 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 €/W_p .

Most of the worldwide research effort is now on thin-film photovoltaic cells. Together with concentrators, these are expected to allow profitable resell prizes 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.*) €/W_p are taken as basis.

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

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

¶ 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.(quoted in [35])

* Especially in reports on defense driven research, e.g. in some editions of [33].

† e.g. piezoelectric polyimide thin-film material actively controlled via an electron gun to constantly adapt its shape.

Hydrogen generation For this assessment, hydrogen is produced via water electrolysis with a proton exchange membrane (PEM) electrolyser. Maddy et al.[36] 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.[37]

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.[38] Their operating costs have been estimated at 2.2 kWh/kg.

2. Energy Transportation

HVDC lines The current cost of HVDC power transmission lines is about 70 €/(kW_e · 1000 km) for land lines and 716 €/(kW_e · 1000 km) for sea lines.[39] The cost for the HVDC stations amounts to 60 €/kW_e 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.

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, 19, 40] 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).[22]

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.[22] 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 €/(kW_{H₂} · 1000 km). These values are taken for the conservative estimates, while the *advanced* values estimate the cost of hydrogen pipelines in 2020 equal to the one for existing gas pipelines, 103 €/(kW_{H₂} · 1000 km).^{**}

3. Energy Storage

Hydrogen storage Only underground hydrogen storage was taken into consideration. Wurster et al. estimate the cost of underground storage at about 3 – 8 €/kg.[38, 41]

4. Plant Costs

Based on the above assumptions and the technical choices described in section III, Tab. VIII list the resulting total costs for all the considered options. The actual

TABLE VII: Cost estimates.

Plant	cons. adv.		
trough surface	215	107	€/m ²
thermal plant (trough)	850	850	€/kW _e
PV surface	2	1	€/W _p
PV surface	294	150	€/m ²
Transportation			
HVDC land line	70	56	€/(kW _e · 10 ³ km)
HVDC sea line	716	572.8	€/(kW _e · 10 ³ km)
HVDC stations	60	48	€/kW _e
H ₂ pipeline (0.25 m)	154	103	€/(kW _{H₂} · 10 ³ km)
H₂ Production and Storage			
H ₂ prod. (PEM)	1,621	333	€/kW
H ₂ compressor	800	650	€/kW(20 MPa)
underground storage	8	3	€/kg

TABLE VIII: Cost estimates of terrestrial plant options. (all values in B€, incl. capital costs)

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

receivers and the fuel cells represent the most important cost factors for the PV and trough options. The cost estimates in Tab. VIII include approximative capital costs of 20% of the total installation costs. In a next step, a more detailed analysis with annual capital cost estimates is required.

Tab. IX shows the cost of the peak power plant, covering the entire excess electricity need, leaving to conventional base load powerplants a completely constant power supply curve. This option would be particularly suitable for a nuclear/solar combination since nuclear plants operate preferably at constant power levels.^{††}

^{**} These costs are higher than the one for electric lines, contrary to the claim that over long distances, energy transportation in form of hydrogen would be cheaper.[14, 36]

^{††} In order to cover the saved power production capacity with modern coal plants, an approximate investment of 145 B€ would be required, to which the cost of the coal, its transportation and associated environmental costs due to the pollution would have to be added.

TABLE IX: Cost estimates of terrestrial 150 GW peak load plant options. (all values in B€; incl. capital costs)

		PV		trough	
		cons.	adv.	cons.	adv.
with storage	<i>min</i>	2,053	924	1,894	1,005
	<i>max</i>	2,735	1,069	2,576	1,150
H_2 plant	<i>min</i>	2,262	969	2,104	1,049
	<i>max</i>	2,921	1,109	2,762	1,189

In this case, the transport lines (electric or H_2) would not be used to their full capacity most of the time. However, the reduced storage capacity needs leave the total cost of this option only slightly higher than the 80 GW options (Tab. VIII) while selling power almost exclusively at peak load prizes.

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, 42] 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 GW_e rectenna (120 km², circle of 6 km radius), but inclusive of capital costs (4% p.a.).

Tab. X summarises the cost estimates for the European Sail Tower concept.[8] Including the development and operations efforts, the 5 GW_e option amounts to 334.6 B€, higher than the comparable terrestrial plant (Tab. VIII). The 80 GW_e option amounts to 1,386 B€, lower than the conservative but higher than the optimistic terrestrial plant (including H_2 storage) (Tab. VIII). The larger the plant gets, the more favourable the space option. For the 500 GW_e 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.

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,

TABLE X: European Sail Tower Concept cost estimates

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

^alifetime estimation: 30 years

^bPower distribution lines not included

^cvalues in brackets include land cost estimates

the land costs would be 0.5, 8 and 55 B€.

NASA's Fresh Look Study Options The single solar disc (case 1) and the MEO sun-tower (case 5) were chosen as comparable scenarios in the NASA Fresh Look study.[25]

The 64,500 ton solar disc delivers 5 GW_e to a single receiver site, assumed in proximity to a large city. NASA estimates the total cost for the space section at 22 B€/unit, with 2.5 B€ non-recurring costs. The cost of the ground segment was quantified at 3.9 B€ and the development and production of the two heavy lift launch vehicles was estimated at 27.5 B€. Another 8 and 8.5 B€ was assumed for non-recurring capability and in-space transportation technology costs. The total cost for the space and ground system is estimated at 64 B€, equal to the optimistic terrestrial plant option.

The NASA MEO suntower concept (case 5), delivering also about 5 GW_e for a large city was estimated at about 86 B€, with much lower Earth-to-Orbit (E2O) development costs (no unique heavy launch vehicle) but higher costs for the space segment. Compared to the terrestrial options, the suntower ranges between the cost of the conservative and optimistic PV and trough options. (Tab. VIII)

VI. 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. (Tab. VIII)

TABLE XI: Orbital parameters of three options.

	option 1	option 2	option 3	
apogee alt.	7,838.35	39,954.48	20,182.46	<i>km</i>
perigee alt.	523.50	500.00	20,182.46	<i>km</i>
eccentricity	0.3464	0.7414	0	
inclination	116.57	63.4	98.0	<i>degree</i>
argum. of perig.	270	270	0	<i>degree</i>
lon.asc.node	202.82	314.96	9.0	<i>degree</i>

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 Tab. VIII are approx. 50 – 100 $B\text{€}$ and 700 – 1,600 $B\text{€}$ 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.

Space Augmentations 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.

2nd Ground Station 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 12 h 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 40°N and 112°E. 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^2a , 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.

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.

The main orbital parameters of the three options are summarized in Tab. XI. Access times are calculated respecting maximum steering angles of 30° and transmission possibility only during full solar exposure of the space plant.

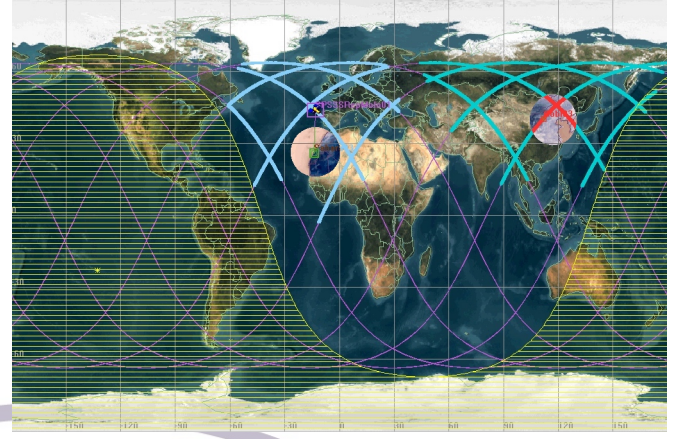


FIG. 4: Option 1 Molniya orbit. (region of ground-stations inverted, January 21 : 00 GMT, solar irradiated areas marked with horizontal lines, access periods in bold)

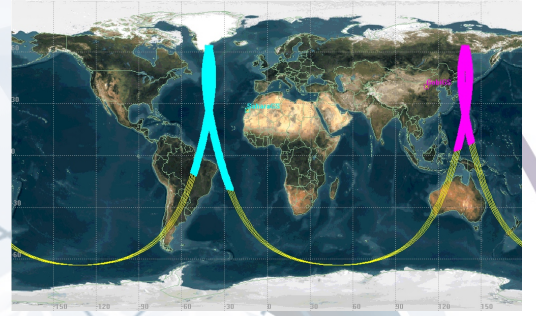


FIG. 5: Option 2 Molniya orbit (January).

Sun-synchronous repeating Molniya orbit This orbit is chosen in order to allow for a daily repeating ground track repeating local times. The maximum altitude for sun-synchronous repeating ground track orbits however reduces the total time of transmission to the Sahara plant to only 30 to 45 minutes. The high eccentricity allows on the other hand a long stay over the northern hemisphere where both plants are located, by accepting an apogee altitude of 7,827 km, possible drag problems and increased mass for attitude control due to the low perigee.

Access times are listed in Tab. XII. With about 45 min-

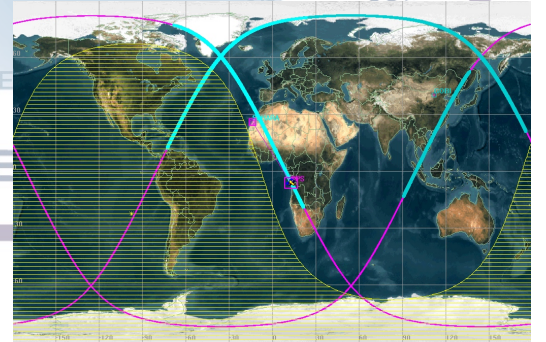


FIG. 6: Option 3 high circular orbit (January 18 : 40 GMT).

TABLE XII: Option 1: Sahara and Gobi plant; access times.

Sahara Plant			Gobi Plant		
start	end	duration	start	end	duration
GMT		(min)	local time		(min)
10:00	10:35	35.2	07:56	08:28	31.7
12:39	13:28	48.2	10:32	11:27	55.0
15:22	16:03	41.0	13:14	14:12	58.0
17:53	18:35	41.9	15:53	16:51	57.7
20:33	21:18	44.9	18:35	19:32	57.1
23:33	23:56	23.2	21:33	22:13	39.3

TABLE XIII: Option 2: Sahara and Gobi plant; access times.

	Sahara Plant			Gobi Plant		
	start	end	duration	start	end	duration
	(GMT)		hours	(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
	20:11	01:38	5.5			
July	04:40	15:56	11.3	23:43	10:39	10.9
October	06:24	11:51	5.4	23:15	09:19	10.1
	15:49	02:40	10.9			

utes, the Sahara access durations are clearly not sufficient for a total coverage of the evening demand. However, the fast revisiting times allow for only minimal storage capacity needs. Due to the higher latitude, the daily repeating access times for the Gobi plant are slightly higher (almost 1 hour). They also cover well the expected local evening demand.

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 plant stays most of the orbital time over the northern hemisphere. January ground tracks are shown in Fig. 5. The effect of the high eccentricity to the gravity gradient stabilised SPS requires some additional analysis.

As shown in Tab. XIII, both plants are accessed during the (local) evening peak times in winter months. During summer, the space 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 Tab. XIII, the ground track of the satellite is only *close* to be sun-synchronous, thus slowly drifting eastwards. The drift speed was chosen to allow for

a 1-year phase repetition, leading to evening peak coverage in winter and morning to afternoon coverage during summer.

high repeating circular orbit A circular MEO orbit at 26,560 km altitude, 98° inclination would have a repeating ground track passing close to both ground stations. With an ascending node at 9° longitude, the local pass over time at the Sahara-based receiving site is around 20:00 GMT in winter months. The daily evening power delivery duration would be about 2h45, just enough to cover the evening peak demand.

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).

For the space mirror options, a simple model was made for rough estimates. Instead of the 0.016 kg/m² derived from the *Zvezda/SolarKraft* experiments, 0.1 kg/m² were assumed for advanced thin film mirrors with active elements. A 5 GW_e mirror would roughly need a surface of 37 km², assuming space losses of 50% and 20% ground conversion efficiency. The ground spot in case of orbit option 1 being more than 80 km in diameter with < 1 W/m² power density, in-space focussing and additional optics would be required. Assuming a specific mirror mass of 0.1 kg/m² and doubling the mass for optics and structure, the total space section mass would be about 7,300 tons, only 10% of the μ -wave 5 GW sailtower option.

Several of these options are currently assessed within the ESA Advanced Concepts Team in close cooperation with European industry and academia. A significant portion of the first phase of the ongoing European SPS Programme Plan is dedicated to the integration of space and terrestrial solar power plants, taking into account the requirements of a developing European hydrogen economy.[43]

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