SPACE AND TERRESTRIAL SOLAR POWER SOURCES FOR LARGE-SCALE HYDROGEN PRODUCTION - A COMPARISON

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The present work examines new ways of large-scale hydrogen generation via space assets. Solar power satellites, large structures in Earth orbit converting solar energy via photovoltaic cells 24h/day into electricity, that is immediately transmitted via electromagnetic waves to dedicated Earth receiver sites, constitute a greenhouse-gas emission free power plant option able to overcome many of the drawbacks of large-scale terrestrial solar power plants.

This paper presents a comparison of terrestrial large-scale solar power plant solutions with space-based solutions by taking into special consideration their respective integration into a hydrogen-based economy. The application focus of the paper is on the larger continental European situation.

Keywords: Solar Power Satellites, solar hydrogen, desert PV Plants, space

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 21^{st} 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 planers 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.

To this extent, a comparison of space and terrestrial solar power solutions is presented, not in order to trade them off, but to show their complementarities and their combined potential. In a situation where terrestrial as well as space power plants still play an minor part in strategic energy considerations, it seems strange that the many common points of terrestrial and space solar plant options did not yet lead to a stronger cooperation between the respective research groups.

On the contrary, the two research communities seem to at the best ignore, at worst devaluate each other for the alleged benefit of the own option. This paper tries to highlight mutual benefits and the complementarity of the concepts.

The scope of the considerations is on the wider European context.

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

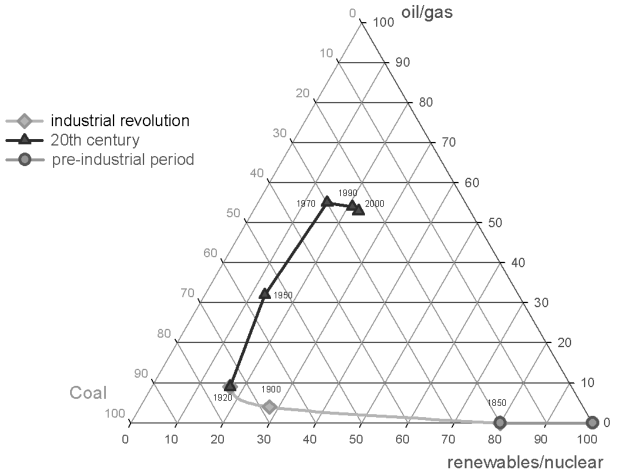

FIG. 1: 20^{th} *century energy triangle.*

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 19^{th} century.

Plotting the proportional supply share of 1. renewables/nuclear sources, 2. coal and 3. oil and gas as done in Fig. 1, shows that this situation occurred at least two times during the 20^{th} 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 20^{th} century. To a lower extent, the oil crisis of the 70s had a similar effect, when the introduction of nuclear energy lead to the levelling of the oil and gas share at about 60%. Currently a trend from oil to gas is observed (not shown in Fig. 1), in line with the successive reduction of the carbon content of fuel. (C:H ratio: wood: $\sim 10:1$, coal: $\sim 2:1$, oil: $\sim 1:2$, gas: $\sim 1:4$)

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

One section will describe a possible solar power plant in northern Africa, delivering energy in form of electricity or hydrogen to Europe.

For the space option, the most recent European and international solar power plant concepts are taken as a basis to be compared.

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, 6] 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.

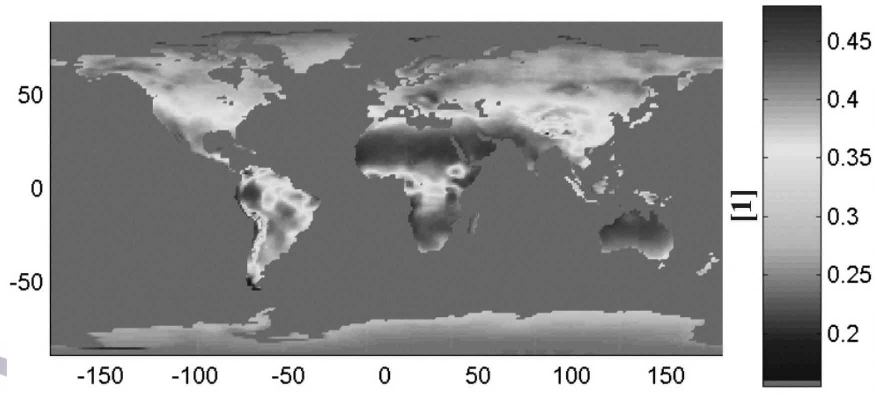

FIG. 2: *Efficiency of solar thermal troughs.(data: EZMW and NCEP)[9],[10]*

Power Levels Seboldt et al. designed the fully deployed system of the European Solar Sail Tower SPS concept to deliver 513 GW_e[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 MW_e, 18 sail towers transmit to one 5 GW_e receiving antenna. 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. [8] 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. 3, right y-axis) leading to the predicted maximum load *levels* of 500 and 430 GW respectively.[5, 6]

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. 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. A location in the western Sahara desert(26°N, 14°E) with an averaged daily solar irradiance of 280 W/m^2 (2455 kWh/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 [11] — were crossed with the sunrise and sunset data obtained from the Astronomical Department of the US Naval Observatory [12] 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. 3 shows the hourly irradiation data for the chosen location as well as the 2001 European electricity load profiles.

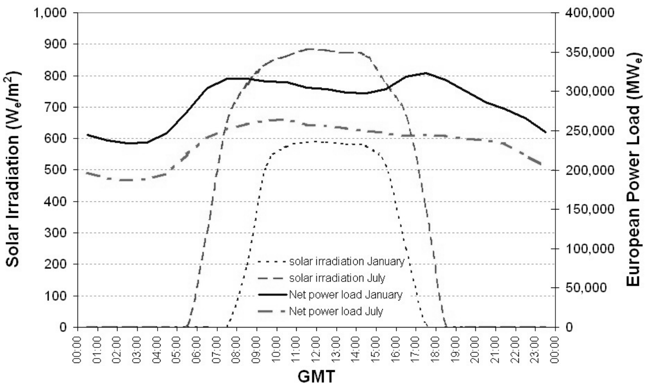

FIG. 3: *Typical winter and summer day solar irradiation and European electricity load profiles.*

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 $\sim$ 16% [13], 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 (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, in turn driving a turbine. Solar tower sizes are currently designed for power levels in the order of 200 MW_e.[14]

For this assessment, dimension and cost calculations for solar thermal plants were only done for trough systems. The extension to solar tower plants is straight-forward, but due to reported higher electricity generation costs not done. In the case of alternative hydrogen production methods, solar tower systems might well be advantageous over trough systems due to their higher operating temperature. Such a trade-off still needs to be done.

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).

* 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.

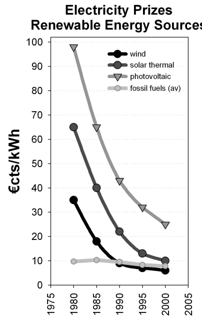

FIG. 4: *Actual electricity cost reductions of renewable energies between 1980 and 2000. (data: NREL)*

This trend is demonstrated in Fig. 4, showing the NREL estimates of electricity production cost reductions for different renewable energy sources from 1980 to 2000.

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. At the end of 2000, the worldwide solar photovoltaic capacity was slightly over 800 MW, with a steady growth of the total installed capacity between 20 and 31% annually from 1992 and 1999. Since 1999 the annual increase is about 37%, peaking as high as 43.8% in 2002, mainly due to national programmes in Japan and Germany (European growth rate 2002: 56%).[15, 16]

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.[17].

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.[18, 19, 20]

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.

There are essentially two process configurations possible for this option:

1. Ambient temperature electrolysis, when concentrated solar energy is used to generate alternating current electricity running an electrolyser.

[‡] 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.

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 electronlysis	**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	$kWh/m^3(at 20MPa)$

[a]Future levels are expected to be significantly higher. Taking only the electrolyser efficiency, current levels are $\geq$ 75%.[22]

2. High temperature electrolysis of steam, when the concentrator supplies at the same time the heat and the electricity to convert steam at about $1273K$ to hydrogen and oxygen.

Both options are currently considered for large scale H_2 production, since there seems to be little total cost differences.

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 $O_2 + H_2$ 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 O_2+H_2 driven turbines and completely reversible PEM fuel cell systems still needs to be done. §

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.[23] 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.[24]¶ If not calculated in detail (as done e.g. for

§ Advanced production methods based on photobiological processes (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. [21]

¶ 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	$tons$

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 transformator 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 (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 $8,900\ kg/h$.[23, 25]** 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.††[26]

For a more thorough assessment, the pumping power N needs to be calculated via equation 1.

$$N = V_0 \Delta p = \frac{\pi}{4} D^2 v \frac{1}{2} \rho v^2 \zeta, \tag{1}$$

with

$$\zeta = \frac{0.31164}{R^n}, R = \frac{\rho v D}{\eta}, \tag{2}$$

with V_0 = volumetric flow rate, v = velocity of H_2, Δp = pressure drop, D = pipeline diameter, ζ = resistance coefficient, R = Reynolds number, $n = 0.25$ for turbulent pipe flow and η = dynamic viscosity of hydrogen ($8.42 \times 10^{-6} Pa\,s$).

** 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.

TABLE IV: 80 GW_e *plant without storage.*

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

[a] installation surface in brackets

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.[20]

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 [27]. The emphasis of this study is on hydrogen plants.

The HVDC lines are dimensioned for the highest peak values of the plant, thus not working at full capacity most of the time (winter month, evening, night and morning values).

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 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. 5.

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 $190\,GW$ 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. Fig. 6 shows the resulting January power profile day.

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

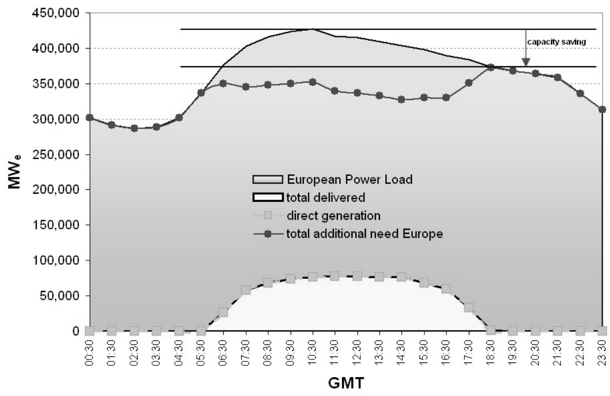

FIG. 5: 80 *GW plant without storage capacity - summer day.*

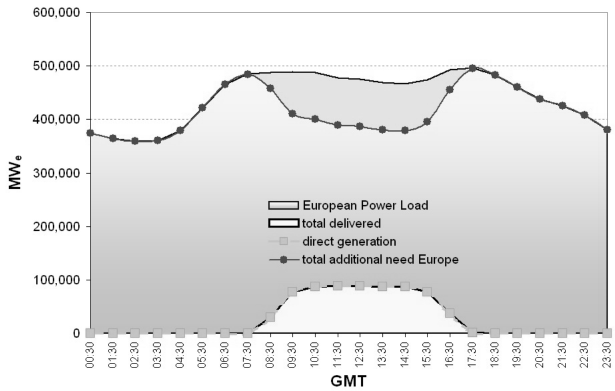

FIG. 6: 190 *GW plant without storage capacity - winter day.*

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.

For comparison purposes, the case of a 5 GW plant is also considered. The specifications are shown in Tab. V.

In a next step, local storage capacities are included.

There are several options, one would be to first use the already existing storage capacities in Europe, especially the water storage power plants in mountainous regions. This option was however not considered for this assessment, where local on-site storage in underground hydrogen reservoirs

TABLE V: 5 GW_e *plant without local storage capacity.*

	January	July	
receiver surface[a]	29(59)		km^2
transport capacity	3	5	GW
total production	19	52	GWh/day
peak power delivered	3	5	GW
directly delivered	19	52	GWh/day
capacity saving[b]	0.0(0.006%)	5.1(1.2%)	GW

[a]installation surface in brackets
[b]percentage of total generation capacity in brackets

TABLE VI: 500 GW_e *plant covering the entire European electricity need in 2020.*

	January	July	
receiver surface[a]	22,481(44,962)		km^2
transport capacity	546		GW
total production	14,804	39,320	GWh/day
directly delivered	4,346	5,694	GWh/day
into storage	10,459	33,626	GWh/day
stored	6,275	20,176	GWh/day
over/under-capacity	0	15,685	GWh/day
H_2 production capacity	1,506	3,482	GW
H_2 production rate	30,166	69,762	t/h
H_2 production	209,556	673,763	t/day
total storage volume	12,662,530	40,712,530	m^3/day
equiv. sphere rad.	145	213	m
total water need	1,886,190	6,064,471	t/day

[a]installation surface in brackets

is taken as basis.

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 size to take into account storage needs and losses.

Since the electricity need in winter is higher and the solar irradiation lower, winter months have to be taken as baseline, accepting an overproduction during summer months. For an in-depth analysis, an optimisation process including also other available power sources (e.g. wind) and storage options (e.g. water storage power plants) would be required.

The main parameters of the system are summarised in Tab. VI. The total receiver surface would cover over 25,000 km^2, equaling 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 general parameters of the plant are similar to the ones in Tab. X. Fig. 7 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 the production of liquid hydrogen for other applications.

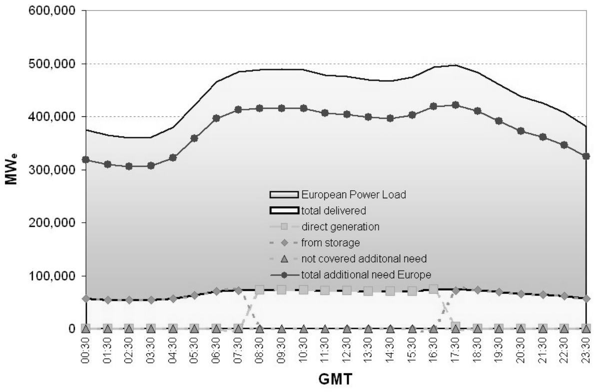

FIG. 7: 80 GW_e *plant — January electric power delivery.*

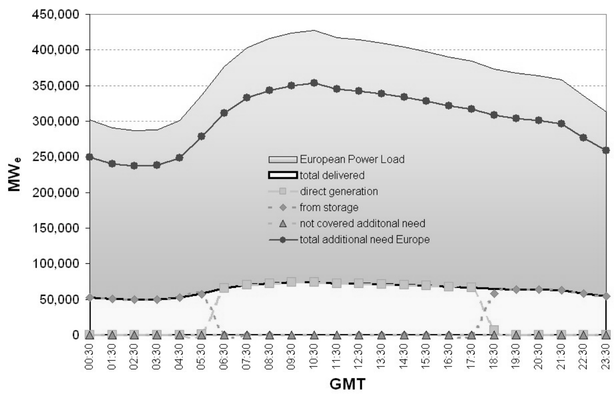

FIG. 8: 80 GW_e *plant — July electric power delivery.*

TABLE VII: 80 GW_e *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 prod. rate	4,525	10,464	t/h
H_2 production	31,433	101,064	t/day
reservoir volume	1,899,379	6,106,879	m^3/day
equiv. sphere rad.	77	113	m
total water need	282,928	909,671	t/day

TABLE VIII: $5\,GW_e$ *storage electricity plant.*

	January	July	
receiver surface	225		km^2
transport capacity	5		GW
total production	148	393	GWh/day
directly delivered	43	57	GWh/day
into storage	105	336	GWh/day
stored	63	202	GWh/day
over/under-capacity	0	157	GWh/day
capacity saving	5	5	GW
H_2 prod. cap.	15	35	GW
H_2 prod. rate	302	698	t/h
H_2 production	2,096	6,738	t/day
reservoir volume	126,625	407,125	m^3/day
equiv. sphere rad.	31	46	m
total water need	18,862	60,645	t/day

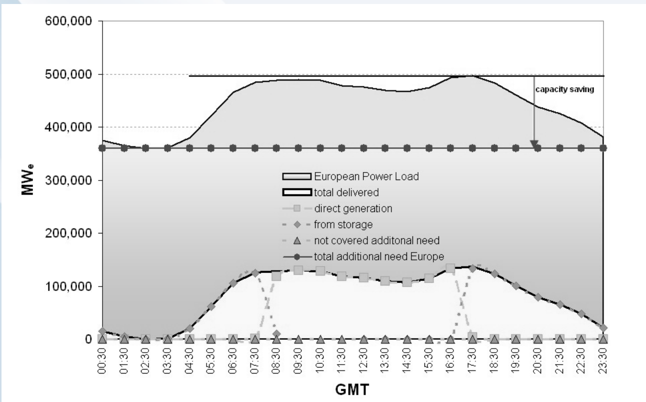

FIG. 9: $150\,GW_e$ *peak load plant — winter day profile.*

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 — 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. 9.

This case is scaled to the winter power demand. The dimensions of the plant are given in Tab. IX. 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,

‡‡ 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.[6]

TABLE IX: 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

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 Tab. X. 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

Space solar power plants were first proposed on an engineering level by Peter Glaser in 1968.[28] 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, 29, 30, 31]) 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. XII shows the main parameter of the European Sailtower concept.[7, 32]

[§§] 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€)

TABLE X: 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		GWh
total production	2,221	5,898	GWh/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

TABLE XI: 5 GW_e *hydrogen plant.*

	January	July	
receiver surface	225		km^2
transport capacity	5		GW
pipeline number	4		
H_2 transport cap.	50		kg/s
pipeline reservoir	8,124		t
	271		GWh
total production	148	393	GWh/day
H_2 total prod.	2,966	7,878	t/day
directly delivered	871	1,141	t/day
into storage (pipeline)	2,096	6,738	t/day
into storage (reservoir)	0	0	t/day
H_2 prod. cap.	397	795	t/h
reservoir volume	0	0	m^3
total water need	26,699	70,914	t/day

For a review and comparison of recently proposed solar power plants with μ-wave power transmission, it is referred to [31] and [27]. The present assessment tries to focus on the principal characteristics of laser based space solar power plants.

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 GWh) to

TABLE XII: European Sail Tower Concept characteristics.[32]

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

2001 (339 GWh).[33] The installed capacity within the EU grew even at a rate of 37.7% in 2002,[34] but the total energy produced is still extremely low.[15, 16]

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.[35] 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.[35] 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 $840-890\,nm$ 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 loosing 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 $31,000\,m^2$; $0.016\,kg/m^2$). 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 $\$/kWh$ while the ones installed in 1991 managed to produce at rates as low as 0.12 $\$/kWh$.[37] 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. XIII.‡

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* Especially in reports on defense driven research, e.g. in some editions of [36].

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

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

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 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.*) €$/W_p$ 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.[41]

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.*) €$/kW$.[42] 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 €$/(kW_e \cdot 1000\,km)$ for land lines and 716 €$/(kW_e \cdot 1000\,km)$ for sea lines.[43] The cost for the HVDC stations

§ The most powerful PV grid electricity plants being in the order to some hundreds of kW (e.g. in Sacramento (US)[38]

¶ 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 [39])

TABLE XIII: *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	€$/(kW_e \cdot 10^3 km)$
HVDC sea line	716	572.8	€$/(kW_e \cdot 10^3 km)$
HVDC stations	60	48	€$/kW_e$
H_2 pipeline (0.25 m)	154	103	€$/(kW_{H_2} \cdot 10^3 km)$
H_2 Production and Storage			
H_2 prod. (PEM)	$1,621$	333	€$/kW$
H_2 compressor	800	650	€$/kW (20\,MPa)$
underground storage	8	3	€$/kg$

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.[18, 20, 23, 44] 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).[26]

Veziroglu et al. estimate that the cost of hydrogen pipelines would be 50% to 80% higher than that of a natural gas pipelines.[20] True evaluates the cost of a $100\,cm$ gas pipeline at $62,000$ €$/km$.[26] 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 €$/(kW_{H_2} \cdot 1000\,km)$. 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 €$/(kW_{H_2} \cdot 1000\,km)$.[**]

3. Energy Storage

Hydrogen storage Only underground hydrogen storage was taken into consideration. Wurster et al. estimate the cost of underground storage at about $3-8$ €$/kg$.[42, 45]

4. Plant Costs

Based on the above assumptions and the technical choices described in section III, Tab. XV list the resulting total costs for all the considered options. As an example Tab. XIV shows the detailed

[**] 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.[18, 40]

TABLE XIV: *Cost estimates of the terrestrial* 550 *GW +storage plant options. (all values in B€; capital costs not included)*

		PV		troughs	
		cons.	adv.	cons.	adv.
	receiver	6,609	3,372	4,833	2,405
	plant inst.[a]	661	337	1,685	1,685
Power plant		7,270	3,709	6,519	4,091
	lines	96	76	96	76
	stations	66	52	66	52
Energy transport		161	129	161	129
H_2 gen.	(min)	2,440	501	2,440	501
	(max)	5,644	1,159	5,644	1,159
compr.	(min/max)	15/49	12/40	15/49	12/40
cost	(min)	**9,889**	**4,353**	**9,137**	**4,734**
	(max)	**13,130**	**5,043**	**12,378**	**5,325**

[a]Power management and thermal plant

cost splitting of the 550 GW plant designed to supply the entire European electricity need in 2020.

The receivers and the fuel cells represent the most important cost factors for the PV and trough options. The cost estimates in Tab. XV 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. XVI 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.[††]

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. XV) while selling power almost exclusively at peak load prices.

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.[32, 46] The development costs include the development of a heavy lift launch vehicle (20 $B€$,

[††] 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 XV: *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	*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 XVI: *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	*min*	2,053	924	1,894	1,005
	max	2,735	1,069	2,576	1,150
H_2 plant	*min*	2,262	969	2,104	1,049
	max	2,921	1,109	2,762	1,189

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 $€/m^2$) per 5 GW_e rectenna (120 km^2, circle of 6 km radius), but inclusive of capital costs (4% p.a.).

Tab. XVII summarises the cost estimates for the European Sail Tower concept.[7] Including the development and operations efforts, the 5 GW_e option amounts to 334.6 $B€$, higher than the comparable terrestrial plant (Tab. XV). 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. XV). 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.

TABLE XVII: *European Sail Tower Concept cost estimates.*

development incl. LV		**265**	$B€$
1 sail tower[a]	production	1.24	$B€$
($275\,MW_e$)	E2O transp.	0.92	$B€$
	oper.&maint.	0.044	$B€/a$
	total	**3.48**	$B€$
18 sail towers	production	22.3	$B€$
($5\,GW_e$)	E2O transp.	16.6	$B€$
	oper.&maint.	0.8	$B€/a$
	total	**62.6**	$B€$
290 sail towers	production	360	$B€$
($80\,GW_e$)	**total**.	**1,009**	$B€$
1818 sail towers	production	2,254	$B€$
($500\,GW_e$)	**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)**	$B€$

[a] lifetime estimation: 30 years
[b] Power distribution lines not included
[c] values in brackets include land cost estimates

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 $€/m^2$, 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 $B€$.

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.[29]

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. XV)

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. XV) 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 Tab. XV 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.

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.

2^{nd} **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. XVIII. Access times are calculated respecting maximum steering angles of 30° and transmission possibility only during full solar exposure of the space plant.

TABLE XVIII: *Orbital parameters of three options.*

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

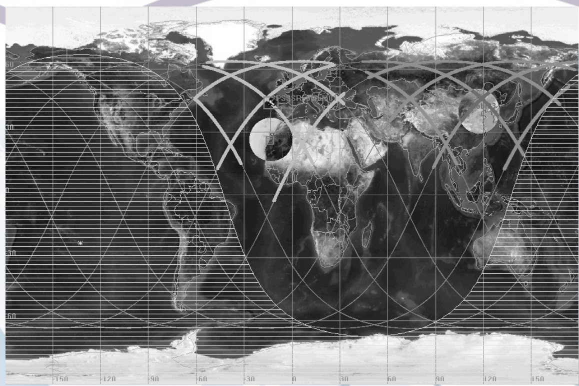

FIG. 10: *Option 1 Molniya orbit. (region of ground-stations inverted, 21:00 GMT)*

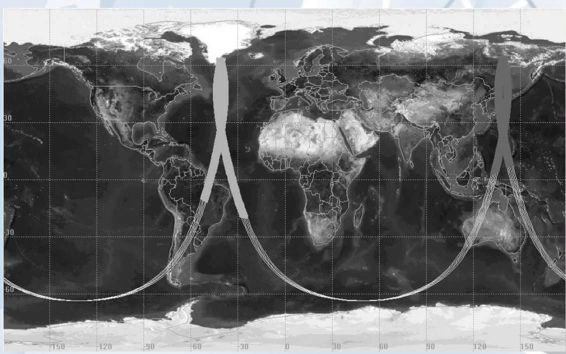

FIG. 11: *Option 2 Molniya orbit (January).*

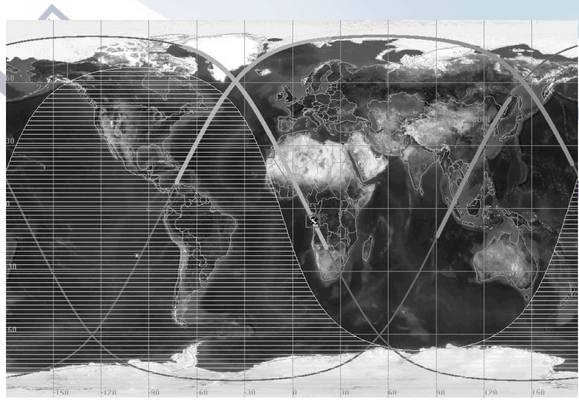

FIG. 12: *Option 3 high circular orbit (January).*

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

Sahara Plant			**Gobi Plant**		
start GMT	end	duration (min)	start local time	end	duration (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

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 of 0.3464 allows on the other hand a long stay over the northern hemisphere where both plants are located and shorter stays over the southers hemisphere, by accepting an apogee altitude of $7,827\,km$.

Access times are listed in Tab. XIX. With about 45 minutes, 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 space solar power plant stays most of the orbital time over the northern hemisphere. January ground tracks are shown in Fig. 11. The effect of the high eccentricity to the gravity gradient stabilised SPS requires some additional analysis.

As shown in Tab. XX, 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 Tab. XX, 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.

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.

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

	Sahara Plant			**Gobi Plant**		
	start (GMT)	end	duration hours	start (local time)	end	duration 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			

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 $0.016\,kg/m^2$ derived from the *Zwezda/SolarKraft* experiments, $0.1\,kg/m^2$ were assumed for advanced thin film mirrors with active elements. A $5\,GW_e$ mirror would roughly need a surface of $37\,km^2$, 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 not even $1\,W/m^2$ power density, in-space focussing and additional optics are required. Assuming an specific mirror mass of $0.1\,kg/m^2$ and additional 100% optics and structure mass, the total space section mass would be about $7,300\,tons$, only 10% of the μ-wave $5\,GW$ sailtower option.

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