

SOLAR POWER FROM SPACE – AN ENERGY SOURCE MEETING THE DEMAND OF A HYDROGEN-BASED SOCIETY

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Abstract

In the light of naturally limited fossil fuels and increasing environmental impact of its utilisation, the total increase in worldwide energy consumption will be accompanied by two parallel effects: an increased demand of energy in form of electricity and a separation of energy carriers from the energy sources. The substitution of oil and gas in the global pipelines by hydrogen requires new, abundant and concentrated energy sources for its production.

Among the greenhouse gas (GHG) emission free options, solar power satellites (SPS), collecting solar power 24h/day in space and transmitting it to dedicated receiver locations on Earth constitute one of the most attractive long-term options. This paper analyses the possibilities of SPS to provide the power needs for large scale hydrogen production and investigates its integration into a global hydrogen-based society.

Introduction

Reliable energy supply, meeting the ever increasing demands, is of fundamental importance for prosperous and peaceful worldwide development. While the industrial revolution from the mid 19th century until the first decades of the 20th century was based on coal burning, the development of the 20th century until now relies mainly on oil and gas burning, with a relatively small nuclear portion since the 1970s.

With the discovery of electricity and its over-proportional increase since about a century, the 20th century brought also the separation of *energy vectors* from *energy sources*. Worldwide electricity consumption is expected to further increase stronger than the total energy demand until 2020. The introduction of hydrogen will further decouple energy vectors from energy sources.

Taking into account the environmental impact of the use of fossil sources and the unequal distribution of oil and gas, leading to strong dependence on relatively few supplier regions, there are good reasons to assume that growth of the 21st century should and will be based on the use of renewable and increasingly GHG emission neutral energy sources. Already 2003, while still at a very low absolute level, renewable energy sources are the most rapidly increasing source.

In the long term, we most likely need to build our development on an energy system, that is built on reliable, affordable, abundant and environmentally neutral sources together with as much as possible closed, environmentally neutral energy vector cycles.

Terrestrial renewable power sources receive in an increasing number of countries substantial interest. Space based systems, solar power satellites, on the other hand are still widely considered as too unrealistic to receive significant support. Taking into account the respective specificities and the current trends, space and terrestrial systems could be complementary and can both play an important role in obtaining clean and reliable energy supply for the 21st century.

The introduction of the new energy vector *hydrogen*, will enhance this trend and especially its storability will benefit the development of terrestrial and consequently space renewable energy sources.

Current energy situation

The European Union represents about 16% of the world energy market. In 2000, it imports about half of its energy need and represent in total terms the largest energy-importing region of the globe.

Within Europe, national energy profiles remain very different due to differences in economic structures, local resources, taxes and policy priorities. Regionally, oil is the most important energy source although its share is falling since 30 years, contrary to gas, the share of which constantly increased over the same period. Coal production and use has fallen since the 1970 and is now used mainly for electricity production.¹

Europe's energy projections

European Unions' economy is assumed to grow at 1.9% annually until 2030, accompanied by an annual increase of the total primary energy demand of 0.7%. While the share of coal will continue to decrease, the one of gas will attain the level of oil, around 34%, by 2030. Non-hydro renewable energy sources are expected to more than double their share from 4 to 9%, equalling the nuclear share that – based on current projections about power plant construction – would decrease from today 15 to 8% in 2030.¹ Several of these assumptions are based on business as usual approaches, thus excluding radical changes.

In parallel with the increasing demand, Europe's non-renewable energy reserves are diminishing and their extraction becomes less and less economically viable. As a consequence, the European Commission identified an increasing use of renewable energies as a strategic objective that could address the two main points: 1. energy dependence and 2. environmental and climatic changes caused by greenhouse gases.

Europe's energy dependence

The two trends result in a significant increase of Europe's total energy dependence, from today 50% to about 60 to 70% in 2030.² The enlargement of the Union does not alter this picture significantly, the trend being valid for entire Europe. The consequent potential vulnerability is furthermore enhanced by the dependence on few suppliers, essentially the Russian Federation (gas), OPEC countries (oil), North Africa (gas) and Norway (oil and gas).

Europe's commitment to decrease its emission of greenhouse gases

The European Union is responsible for 14% of the worldwide man-caused CO₂ emissions. At the Kyoto Conference in 1997, it undertook to reduce its greenhouse gas emissions by 8% until 2008/2012 compared to 1990. The current trend however is an about 5% increase, calling for substantial action.²

Solar power from Space

Solar power satellites address many of the above mentioned current aspects of future energy systems. The basic idea dates back to the first space visionaries beginning of the 20th century and was first proposed on an industrial scale and with an engineering approach 1968. Since then several studies have been performed, all showing its conceptual feasibility. However, the abundance of fossil fuels and high investment and development costs, closely linked to high launch costs prohibited significant investments into solar power satellites.

The basic idea is as simple as appealing: to make use of permanent insolation in outer space to produce (via photovoltaics) electricity and then beam this energy via microwave (or laser) to dedicated, large receiver sites on Earth (possible on rectennas (receiving antennas for microwave beams) offshore close to large energy consumer centres).

An artist view of a solar power satellite is given in Figure 1. The figure shows the long, gravity gradient stabilised main trunk with the multiple pairs of thin film quadratic solar cell panels, delivering electricity via superconducting central cables to the phased-array antenna pointing to Earth.

SPS Research Work in Europe

European Network on Solar Power Satellites

The European Union has identified research on sustainable energy as one of its priority research areas for the 6th Framework Programme.³ In order to focus the different European activities on SPS, a European Network on Solar Power Satellites was established in August 2002, following an initiative of the Advanced Concepts Team of the European Space Agency.

The network is composed of representatives from European research institutes, agencies and industry. One of the goals is to position research on the space option of renewable energies in the context of research on sustainable development in Europe.

European Sail Tower SPS			
Orbit	GEO		
Final # 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	magnetron	n
	frequency	2.45	[GHz]
	radius	510	[m]
	mass	1600	[mt]
	energy emitted	400	[MW]
receiving antenna site	final number	103	
	antenna size	11x14	
	site including safety zone	27x30	[km]
power delivered	per SPS tower	275	[MW _e]
	sail tower production	1.24	[B€]
	sail tower transportation	0.92	[B€]
cost	ground antenna per 5GW	18	[B€]
	development (+launch vehicle)	265	[B€]
	oper.& maint.p.a.	0.044	[B€]
	lifetime	60	years
	power gen. cost	0.075	[€/kWh]

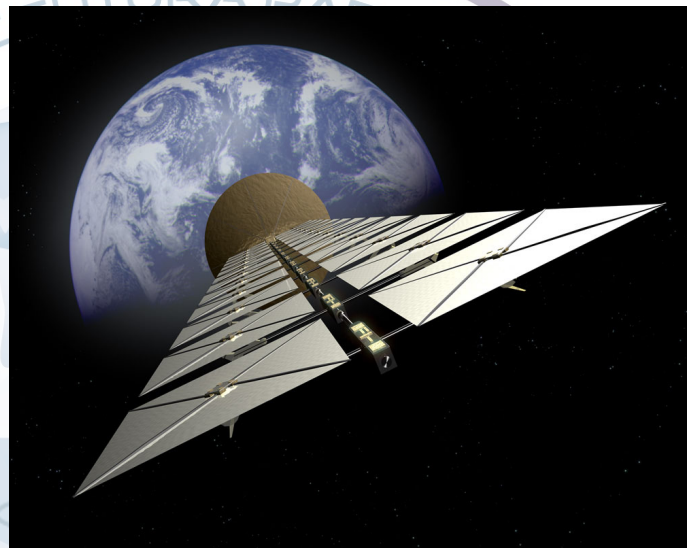
Table 1: Characteristics of the European Sail Tower concept.⁵

The most recent significant European study on solar power satellites was performed by the German Space Agency DLR under an ESA contract in 1999.⁴ Combining thin film technology and innovative deployment mechanisms developed for solar sails with the NASA concepts of space solar towers, a “European Sail Tower SPS” was presented.^{5,6} The main characteristics are summarized in Table 1.

European SPS reference architecture

In parallel to the identification of reference SPS architectures that will serve as reference for system level research, the study will identify technical domains where European laboratories are internationally on the leading edge.

Several studies on SPS until now have shown that there are no technical showstoppers for SPS.^{4,7,8,9} On the other hand, some of the conclusions of these past studies are also that 1. embarking in an SPS endeavour still bears high technological risks, 2. critical technical issues need more research; 3. the total cost of investment are high compared to the late first return on investment, 4. the advantages of the SPS compared to terrestrial solar plants are not obvious, 5. SPS can only be considered as an international effort, 6. launching costs have to decrease by at least an order of magnitude (construction of SPS itself would certainly decrease launching costs; sometimes compared to the chicken-egg problem).



**Figure 1: Artist view of a Solar Power Satellite
(European SPS Tower concept)**

Comparison of Space and terrestrial solutions

In this section, a preliminary order of magnitude for terrestrial alternatives is given by estimations on cost and efficiencies of a hypothetical north African solar power station. It is first assumed that the produced energy will be transported to Europe in form of electricity via power lines. In a second step, the use of hydrogen pipelines will be considered. For this assessment a region in the scarcely populated areas somewhere in the western Saharan desert is taken. The concept tries to rely solely on proven and already available technologies. While in space photovoltaic systems are with current technology the by far most advantageous, the most advanced terrestrial solar power plants are trough concentrators.

North African Solar Thermal Power Plant

Seboldt et al. estimated the final system of the European Solar Sail Tower SPS concept for being capable to deliver 515 GW, the projected consumption of Europe for 2020, equalling also $\frac{3}{4}$ of the additional generation capacity foreseen to be installed between 2000 and 2030. The cumulative investment for this additional capacity is currently estimated at 531 B€ in a business as usual scenario.¹ For comparison reasons, this first assessment is based on a delivered capacity of 500 GW. Smaller units delivering 10 and 5 GW are also presented.

The plant would use solar thermal conversion, since at South European and North African latitudes, direct irradiance is about 25% higher than diffuse irradiance.

The basic concept of a trough system consist in parabolic troughs that concentrate sunlight about 80 times onto a central absorber pipe in the line of focus, where water (or thermal oils) is heated up to 400°C. The generated steam drives a turbine and an electrical generator before condensing and returning into the cycle. Modern plants have additional gas firing capabilities, increasing the per day system efficiency and economic viability of the plant. In this first approach, this option is not included.

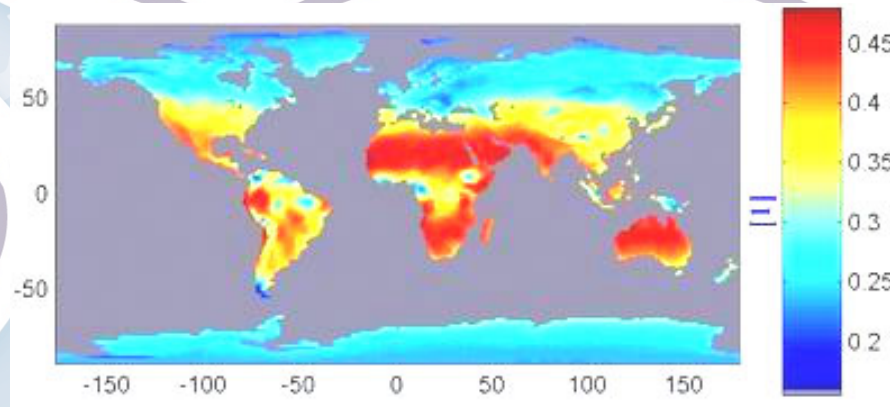


Figure 2: Efficiency of solar thermal troughs (in %)
(data: EZMW and NCEP)^{10,11,12}

The averaged daily solar irradiance at the west Saharan latitude is about 280 W/m². Current solar thermal power plants in the US and Spain operate around an efficiency of 16%^{13,12}, resulting of about 45% efficiency of the parabolic troughs and 35% for the steam engine. (Figure 2) These values are average values, peak values are significantly higher. Projected near-term improvements to 20% seem realistic and are taken as basis for this first assessment.

For the electricity transport to Europe, high voltage direct current (HVDC) cables are considered. HVDC cables are currently the most cost effective power lines over distances exceeding about 800 km. This assessment is based on 2500 km power lines corresponding to the distance between Western Sahara and central west Europe. The reported losses would be in the order of 10% (at full load, the transmission losses are highest and about 4%/1000km, adding 0.6% for the HVDC stations).

Adding up the efficiencies of the different steps and considering the losses, a total receiver surface equivalent to a circle of about 56 km radius (9900 km²) would be necessary to deliver 500 GW_e to Europe.^a

Today, nine solar thermal power plants have been installed, covering a total surface of about 7 km² and delivering around 800 GWh per year. 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.¹⁴ For a plant size for 500 GW, economies of scale would also apply, not taken into consideration here.

^a This represents 0.1% of the Sahara desert size and 3.7% of the size of West Sahara (population density <2 persons/km²)

The current cost of HVDC power transmission lines is about 70 €/kW_e/1000km) for land lines and 716 €/kW_e/1000km) for sea lines, which amounts to about 100 B€ total line installation cost for the described case.¹⁵ The HVDC stations at both end of the line add another 63 B€ (based on 60 €/kW_e). Adding the cost of the power plant itself, 2130 B€ for the solar field and 470 B€ for the thermal power plant (based on the assumption of 215 €/m² for the solar field¹⁶ and 850 €/kW_e for the thermal plant and not taking into account capital cost), these numbers provide an upper limit of 2770 B€^b for any comparable space based power plant. These numbers are based on real data of existing trough power plants.¹⁷ Applying the projected cost reduction for troughs as well as expected near term performance improvements¹⁸, the total cost would be reduced to 1475 B€ (solar field 57%, thermal plant 32%, transmission 7%, HVDC stations 4%). These numbers are in reasonably good agreement with previous published results.¹⁹

At a smaller scale, in order to deliver 10 GW_e to Europe, a receiver surface equalling a circle of 7.1 km radius would be required, totalling about 30 B€ (solar field: 17 B€, thermal plant: 9 B€, transmission 2 B€, HVDC stations 1 B€). The main parameters of the comparison are summarised in Table 2.

Taking into account the significant share of the power lines in the total project costs, the use of hydrogen pipelines has to be considered. As far as known to the authors, no reliable information is currently available on long distance large quantity hydrogen pipeline costs. This assessment is currently investigated and should be further elaborated within the European Solar Power Satellite Programme plan.

The location at the Western Sahara is up to 30 longitude degrees east of central Europe, thus enabling some overlap of the production time with high demand time. Typical European January and July power load profiles over one day in January and in July are compared with estimated summer and winter daily power generation profiles in Figure 3.

	conservative	advanced	
energy delivered	500	10	[GW _e]
solar irradiance	280		[W/m ²]
total plant efficiency	0.20	0.25	
transmission distance	2500		[km]
solar field size	9921	7874	157 [km ²]
solar field size radius	56	50	7 [km]
solar field cost	215	107	107 [€/m ²]
thermal plant cost	2133	842	17 [B€]
power transmission cost	97	97	2 [B€]
HVDC station cost	63	63	1 [B€]
total cost	2766	1475	30 [B€]

Table 2: Summary of terrestrial solar thermal plant option.

^b Based on a lifetime of 30 years, the electricity prize would be 2.11 €/kWh. The inclusion of capital cost, discount rates, Management, operations and maintenance costs would at least double to triple this value. A more thorough assessment is currently being prepared.

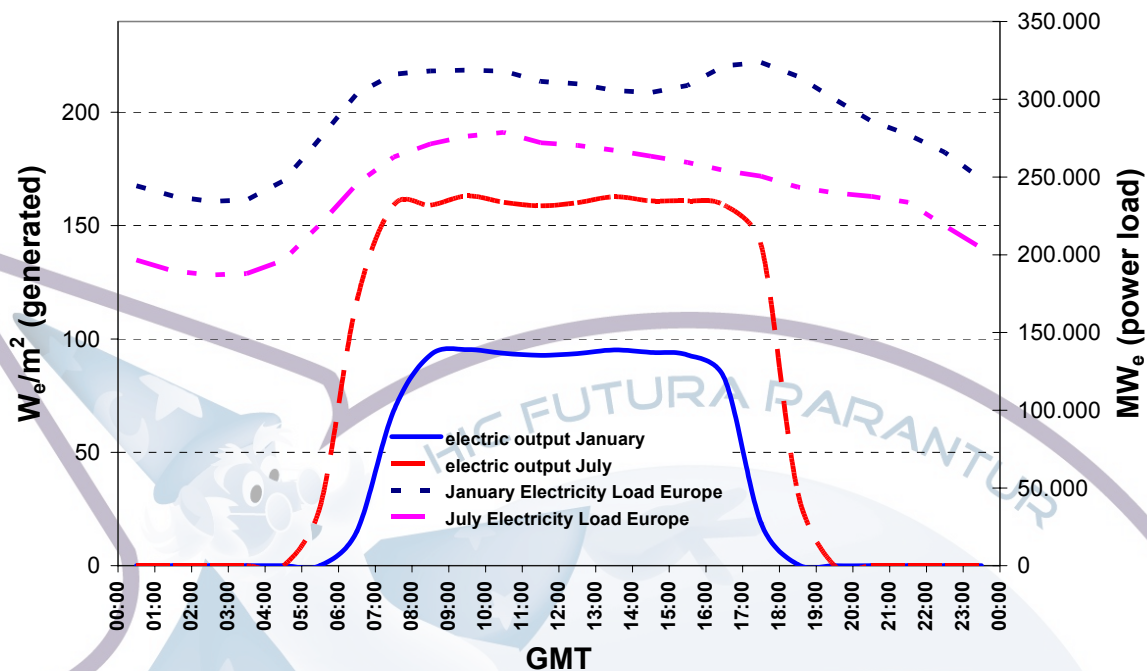


Figure 3: European power load (January and July 2001, data provided by UCTE) and expected electricity generation profiles.²⁰

Figure 4 shows the effect of an 80 GW (summer level) terrestrial power plant in a Western Sahara location on the power load profile for a typical winter and a typical summer day.^c The coloured surfaces are indicating the total energy savings. Energy generation prizes vary by about a factor two between night time, cheap and day time supply. As shown in Figure 4, the studied Sahara plant would serve almost exclusively the high-prize period.

Ideal daily load curves would be flat and constant, without peaks and spikes. Figure 4 shows that the studied plant would flatten the load curve for both months and thus increase the part of cheap baseload power. The second aspect to deal with is the total capacity saving: Such a plant should avoid the construction of additional classic power plants. It is thus necessary to lower the total energy generation capacity demand, dominated by the peak values. As shown in Figure 4, the capacity need would be reduced by about 40 GW for the summer month, but only by about 5 GW for winter days, due to the evening peak in January (mainly caused by private heating and evening home activities).

Importance of hydrogen

The above presented results show the importance of either storage capacities, that could be on-site (e.g. batteries, fuel cells, day time hydrogen production/storage, spinning wheels) or make use of existing storage plants (e.g. water reservoir power stations in mountainous areas) or additional generation capabilities (e.g. gas firing, wind power generation), that could cover the evening peak in winter.

^c For the purpose of this preliminary study, the actual power profile measured in the UCTE network (covering all European countries except Scandinavia, details at: www.ucte.org) on January 17, 2001 and July 18, 2001 are taken as typical winter and summer month load profiles.

Among the different storage options, the generation, local storage and subsequent firing of hydrogen represents the currently most attractive one. Optimisation tradeoffs still have to be done in order to identify the ideal storage dimensions and the share of direct local electricity production versus hydrogen production and subsequent local storage or transport (pipelines, tankers).

The figure shows also the potential of renewable energy plants in connection with hydrogen as energy vector. While electricity needs to be used as much as possible when generated, since all current storage options are expensive or inefficient, the difference between peak and base load power demands would decrease when considering renewable energy stored and distributed in hydrogen.

In the case of solar power satellite concepts, the location on GEO was preferred in most of the studies not at least in order to be able to cover also base-load electricity needs. With the introduction of hydrogen as energy vector, other constellations become much more attractive. With efficient hydrogen storage capabilities, the time of generation is no longer of fundamental importance, and middle Earth orbit constellations, producing at several locations on the Earth surface hydrogen for only several hours per site are possible.

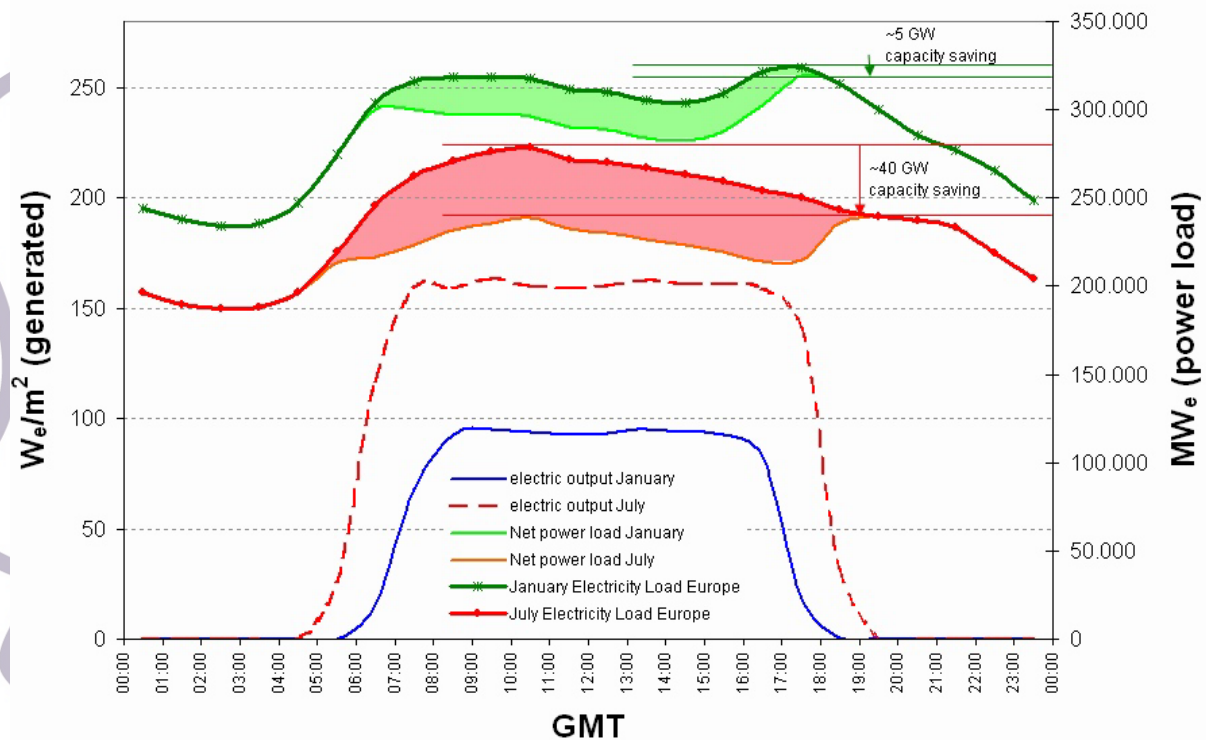


Figure 4: Potential energy generation savings (80 GW plant).

A more detailed assessment is necessary to optimize the size of the plant and the size and kind of storage facilities.

The presented estimations are preliminary in order to give reference orders of magnitude for comparable space systems; a more detailed study taking into account energy storage, discount rates, capital, maintenance & operation and management cost is under way. In addition to the evident environmental benefits, financial benefit due to trade with GHG emission rights as foreseen by the Kyoto protocol and the subsequent international conferences on the subject

will have to be taken into consideration. This assessment will also lead to possibilities of suitable integration of space and Earth based power plants.

Conclusions

The present paper presented the potential role of solar power satellites as emission free, permanent energy source in a hypothetical energy scenario around 2020+. Based on the expected increase in the use of electricity and especially the introduction of hydrogen as clean, storable and transportable energy vector, the role of terrestrial and space based solar energy sources are discussed. In this frame, the research activities of the European Network for Solar Power Satellites are presented and a preliminary assessment of a complementary terrestrial solar power plant to cover part of Europe's energy need in 2020 is given.

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