SOLAR POWER SATELLITES – EUROPEAN APPROACH

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ABSTRACT

The paper presents a strategic approach to assess the importance of space solar power for securing the increasing energy demand of Europe. Past studies have demonstrated the technical feasibility of solar power satellites (SPS). The significant technical and conceptual progress made since the 1979 SPS reference concept lowered the total cost, the cost-to-first-power as well as the required infrastructure. The resulting expected electricity production costs reach a level comparable to existing terrestrial power plants.

At the same time, significant progress was made for terrestrial solar power plants. This paper describes the recently started European approach to evaluate the potential of space-based power plants to secure the increasing energy demand of the continent, including the comparison to terrestrial solar power plants. A first estimation of the size and cost of a North Africa based solar power plant to deliver electricity to Europe is presented.

Based on European particularities, like its high and increasing energy import dependence and the strong engagement to significantly reduce its emission of greenhouse gases (GHG), the effort of the recently created European Network on Space Solar Power, lead by the European Space Agency (ESA), are described.

INTRODUCTION

Reliable energy supply, meeting the ever increasing demands, are 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.

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, growth of the 21st century should be based on the use of renewable and GHG emission free energy sources.

As a consequence, 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.

EUROPE'S ENERGY SITUATION

Current 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 in the world.
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]

MOTIVATIONS FOR RESEARCH ON SPS

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 CO_2 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 a 5% increase, calling for substantial action.[2]

Non-terrestrial use of solar power satellites

The scope of the study will not be restricted to aspects of solar power satellites for the supply of energy for terrestrial uses. Considerations shall also be given to the possibility for delivering energy to spacecraft in Earth bound orbits, on interplanetary trajectories as well as to lunar or Martian outposts. In the same way, the term solar power *satellite* will include also power stations on the Moon.

The recognition of the importance of renewable clean energy sources and the role SPS could play in approximately 20+ years, provides the long term goal for Europe's SPS research. Realistic investment scenarios and the timeframe of political decisions impose some further, important constraints for success for such a long-term strategy: conceptual flexibility to incorporate major changes in the framework (passage to hydrogen economy, etc) and tangible near term perspectives with attractive potential business cases.

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. 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. For this purpose, a first meeting was held in Paris on August 28, 2002, gathering representatives from European research institutes, agencies and industry engaged in research on SPS.

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

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	
	frequency	2.45	[GHz]
	radius	510	[m]
	mass	1600	[mt]
	energy emitted	400	[MW]
receiving antenna site	final number	103	
	antenna size	11x14	[km]
	site including safety zone	27x30	[km]
power delivered	per SPS tower	275	[MW_e]
cost	sail tower production	1.24	[B€]
	sail tower transportation	0.92	[B€]
	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]

The latest bigger 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.

Since several years, the research group at French La Réunion performs in addition to system level studies, valuable experiments on wireless power transmission.[7, 8] Research on SPS in Europe's major space industries was kept on a stand-by level the last years. Complementary to these system level approaches, European laboratories are pushing technology in many SPS critical domains like high efficient multi layer solar cells, thin film solar cells, low mass μ-wave guides, high efficiency μ-wave generators, large extremely lightweight structures etc.
The current initiative by ESA aims to coordinate and focus these activities. The fist meeting of the Network has established a preliminary roadmap (Figure 1) for the organisation of European efforts:

Roadmap

In a first phase, an assessment of terrestrial solar power plants will provide the economic scale that will serve as frame for the study of space solar power concepts. In parallel, a computerised SPS model will be developed, enabling the comparison of technical aspects of different architecture concepts in an objective manner. A small study on legal aspects of space solar power activities will evaluate the legal constraints. Based on the results of the three studies, phase two will start with a short system architecture trade-off study.

In phase two, the system level trade-off study will identify the most promising concepts. It will furthermore identify the critical technical points of the different systems. The timeframe for this study is the first half of 2003.

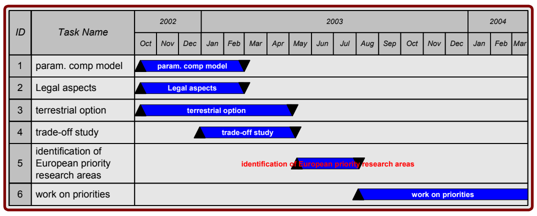

Figure 1: Proposed European SPS roadmap.

The comparison of the 1979 reference system with the solar disc and the solar tower concepts developed during the NASA "Fresh Look" study shows the enormous improvement potential. It seems clear that there is still much room for new and innovative concepts, capable of improving the return/investments ratio and lowering the technical and operational risk. Considering furthermore the fast technological progress since the "Fresh Look" study[9], the European effort will built upon these results with the aim to achieve substantial improvements.

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.[4,9, 10, 11, 12] 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).

Identification of key areas

The next step after the system architecture level trade-off study will consist in enhanced research on two to three key areas. For this phase, prior international coordination leading to a reasonable repartition of tasks would be highly advantageous. Without reconsidering the entire model, these efforts that could begin as early as mid 2003, would address points 1 and 2 above by gradually lowering specific technological risks. The entire SPS model would be kept and updated continuously at the system level.

This phase will then proceed from the pure study level to actual experimental setups, most probably first on-ground and subsequently on a small scale in space. Such small scale demonstrator missions should take as much as possible advantage of existing infrastructure, e.g. WPT to or from the ISS. As stated above, one of the major drawbacks of SPS are the high development costs. The success of this phase will therefore highly depend on the ability to show actual spin-offs and dual use possibilities.

Economic aspects

Contrary to the approach chosen for the "Fresh Look" study, the economic aspects will play only a minor role in the first phases. The emphasis will be on innovative technical solutions.

Nevertheless, the work on the space system will be guided by the constraint that is has to be advantageous or at least competitive to terrestrial alternatives as demonstrated during the first phase.

COMPARISON WITH TERRESTRIAL SOLUTIONS

A preliminary order of magnitude for terrestrial alternatives is given by estimations on cost and efficiencies of a North African solar power station described in the next paragraph. For this assessment a region in the scarcely populated areas somewhere in the western Saharan desert is taken. The concept is relies solely on proven and already available technologies.

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 ¾ of the additional generation capacity foreseen to be installed between 2000 and 2030. The cumulative investment for this additional capacity is estimated at 531 B€.[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. While photovoltaic systems can use also diffuse irradiance, solar thermal plants need the direct part. Between the two major concepts for solar thermal plants, the parabolic trough collectors would probably be preferred over the power tower concept, due to the large area.

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.

The averaged daily solar irradiance at the west Saharan latitude is about 280 W/m^2. Current solar thermal power plants in the US and Spain operate around an efficiency of 16%[13,16], 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.

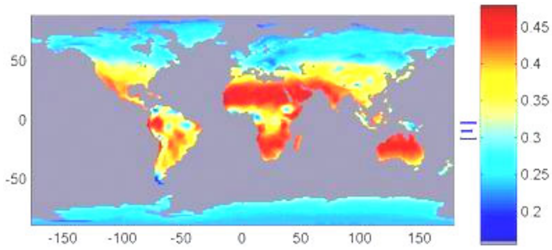

Figure 2: Efficiency of solar thermal troughs (data: EZMW and NCEP)[14,15,16]

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 km^2) would be necessary to deliver 500 GW$_e$ to Europe.*

Today, nine solar thermal power plants have been installed, covering a total surface of about 7 km^2 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.[17] For a plant size for 500 GW, economies of scale would also apply, not taken into consideration here.

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.[18] 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

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

of 215 €/m² for the solar field[19] and 850 €/kWh for the thermal plant and not taking into account capital cost), these numbers provide an upper limit of 2770 B€[†] for any comparable space based power plant. These numbers are based on real data of existing trough power plants. [20] Applying the projected cost reduction for troughs as well as expected near term performance improvements[21], 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.[22]

Table 2: Summary of terrestrial solar thermal plant option.

	conservative	advanced		
energy delivered	500		10	[GW_e]
solar irradiance	280			[W/m²]
total plant efficiency	0.20	0.25		
transmission distance	2500			[km]
solar field size	9921	7874	157	[km²]
solar field size radius	56	50	7	[km]
solar field cost	215	107	107	[€/m²]
	2133	842	17	[B€]
thermal plant cost	850			[€/kW_e]
	472	472	9	[B€]
power transmission cost	97	97	2	[B€]
HVDC station cost	63	63	1	[B€]
total cost	**2766**	**1475**	**30**	**[B€]**

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**.**

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.

[†] Based on a lifetime of 30 years, the electricity prize would be 2.11 €cts/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.

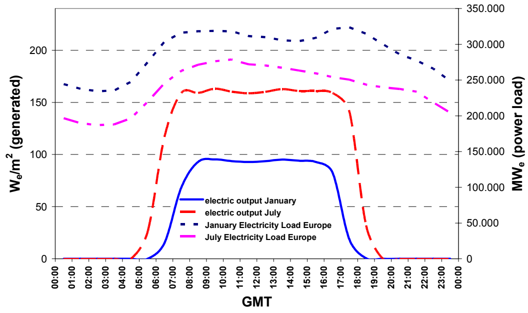

Figure 3: European power load (January and July 2001, data provided by UCTE) and expected electricity generation profiles.[23]

Figure 4 shows effect of an 80 GW (summer level) power plant in a Western Sahara location on the power load profile for a typical winter and a typical summer day.[‡] 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 lead 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 classis 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).

The results shows 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.

[‡] 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.

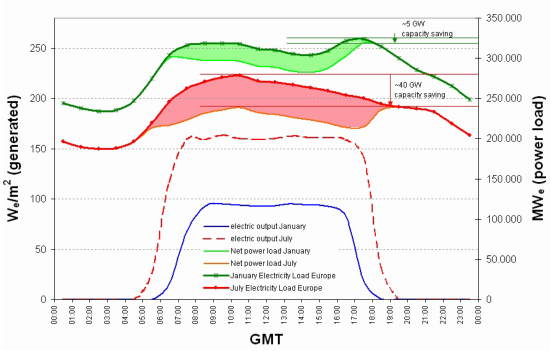

Figure 4: Potential energy generation savings (80 GW plant).

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 has outlined the institutional and technical frame for the research activities of the European Network for Solar Power Satellites. A near-term roadmap was presented, highlighting the priorities of the ESA lead effort. For the purpose of a first comparison with existing SPS concepts and to provide a potential economic frame for European SPS activities, a preliminary assessment of a terrestrial solar power plant to cover part of Europe's electricity need in 2020 is given.

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