Advanced Space Technology for 21st Century Energy Systems: Solar Power from Space

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***Abstract*- Terrestrial solar power is one of the fastest growing energy sectors with high growth rates sustained over more than a decade (especially in Europe) and very promising forecasts.**

Since 30 years the idea of a large solar power plant in Earth orbit, transmitting energy to Earth-bound receiver sites enjoys periodic attention from energy and space entities. All studies concluded the principal technical feasibility of the concepts and gradually improved their power to mass ratio. No substantial development efforts were undertaken however since with current technology space generated electricity costs would still be too high, upfront costs prohibitive and the launcher sector not mature enough to reduce €/kg to orbit costs by the required order of magnitude.

In the past space concepts were mainly compared to traditional energy systems. Based on this background, the Advanced Concepts Team (ACT) at the European Space Agency started a three-phased programme in 2003. The first phase of the programme, the Validation Phase, focused on a comparison of space solar power plant with comparable terrestrial solutions on the one hand and the assessment of the potential of SPS for space exploration and space application on the other.

Space concepts were compared to terrestrial solutions based on equally advanced technology and equal economic conditions for the timeframe 2020/30 in terms of energy payback times, final €/kWh generation costs, adaptability to different energy scenarios, reliability and risk.

I. INTRODUCTION

Space as well as energy are currently perceived as sectors of not only strategic but also increasing importance for this 21st century. Traditionally, they are connected by only weak links.

One of the fundamental issues to be resolved seems to be the identification and implementation of a sustainable energy system, capable to supply the increasing global energy demand necessary to sustain living-standards of developed countries and the development and rise of living-standards of developing countries. The availability of cheap and abundant energy plays a crucial role in enabling the reduction of poverty and development gaps.

The analysis of the evolution of our energy system shows that it underwent several times in the past radical changes (e.g. introduction of electricity, oil and gas, nuclear power) despite its inherent inertia. All of these changes were predictable several decades before their occurrence since they were based on discoveries, the demonstration of their principal feasibility and the subsequent identification/ emergence of needs. Solar power from space was proposed several decades ago, all studies have shown their principal feasibility and the increasing adverse implications of fossil fuel seem to demonstrate the need for a change.[1]

This article tries to contribute to the search for feasible options to be considered for long-term energy systems for this century.

II. MOTIVATION AND FRAME

In 2003, the Advanced Concepts Team (ACT) of ESA has started a multiyear program related to solar power from space. The outcome and findings of the first of the three phases of the program will be presented in this paper. The first phase was dedicated to the assessment of the "general validity" of space concepts for Earth power supply as well as for space exploration applications.[2,3] This paper will focus on the space-to-Earth concepts.

The motivation for the European SPS Programme Plan may be divided into a global and a European dimension.

A. Global Scale

On a global, long-term scale, there seem to exist three major parameters to be considered in connection with the energy system for the 21st century and beyond.

First, according to past experience and all current projections, the global energy need will continue to rise in close connection with the increasing world population.

Second, energy availability and use is closely connected to living standards and development levels, notwithstanding significant regional influence due to climatic conditions and lifestyle. Currently, the average primary energy consumption per capita worldwide is about 17 000 kWh/year. It is more than 5 times higher in North America (100 000 kWh/year) but only 4 and 10 kWh/year for the worldwide most numerous and fasted increasing populations, in Africa and Southeast-Asia respectively.[4]

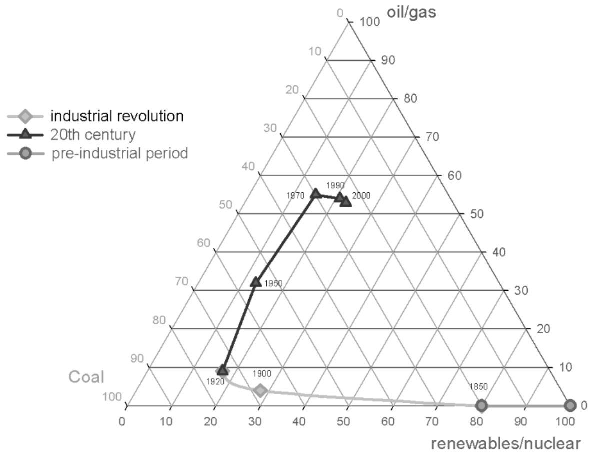

Figure 1: Proportional evolution of primary energy sources.

Therefore, if the natural increase of the total power consumption due to population development should be accompanied by an increase of average living standards in developing countries, the total power need will increase accordingly faster.

Third, a significant part of the global emission of greenhouse gases (GHG) stems from the production of electricity (40%) and from transport (21%). Despite the continuous decrease of carbon intensity over the last 30 years, the decrease has not been and will probably not be sufficient to stabilize or reduce the total CO_2 emissions due to the stronger increase of the total power consumption. According to the International Energy Agency, worldwide carbon-dioxide emissions will rise to $38 \cdot 10^9$ tons per year from currently $16 \cdot 10^9$ tons (increase of 70%).[4]

In addition, new energy needs are likely to alter the situation: one of the currently foreseeable factors is the gradual increase of the fraction of global population subject to severe fresh water stress. Energy-intense desalination plants will be part of the solution to this problem.

Health issues due to metropolitan pollution levels caused by fossil fuel based traffic are likely to add additional arguments for a change of the global energy system.

When trying to anticipate developments, trends derived from past evolution might give valuable indications. Plotting the proportional supply share of 1. renewables/nuclear sources, 2. coal and 3. oil and gas (Fig. 1), shows the gradual change of our main energy sources from those with very high carbon content (biomass, coal; until end of industrial revolutions) to oil and gas for the remaining 20th century.

Since the 1st 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. To a lower extent, the oil crisis of the 1970s had a similar effect, when the introduction of nuclear energy lead to the leveling 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 ratios: wood: ~10:1, coal: ~2:1, oil: ~1:2, gas: ~1:4)

Extrapolating this trend, the curve will approach the lower right corner of the triangle shown in Fig. 1, dominated by sustainable and carbon-neutral energy sources.

When trying to position space energy systems in the proportional triangle in Fig. 1, these would be located in the extreme lower right corner. Due to the absence of hydrocarbons, and thus stored solar energy, only two energy sources are available in space: solar and nuclear. Therefore, taking the energy triangle of Fig. 1, space energy systems are not located where any future sustainable terrestrial system will need to be positioned but the conditions in space are even more stringent. Converted solar energy like hydroelectric, the largest contributor of renewable energy, biomass and wind power (except on some planetary surfaces) are not available in space. Only primary solar power in form of solar irradiation can be used together with the most concentrated form of energy available at the moment: nuclear power.

B. European Dimension

Looking at the more restricted European picture, the following main parameters are taken into account:

- Renewal of large fraction of power plants;
- Increasing energy import dependence;
- Required reduction of greenhouse gas emissions.

A significant portion of European power plants have been built 30 to 40 years ago and reach the end of their nominal lifetime. Against this background a number of European countries have recently started an energy debate on the choices of the future European energy mix.[5]

The International Energy Agency estimates the required investment into the construction of new power plants to substitute part of the ageing ones to be 531 B€ until 2020.[4]

The European Commission and many European countries are actively and substantially supporting the gradual increase of the total share of renewable energy sources.

The European Commission has set a very ambitious target of doubling the share of renewable energy consumption from the current 6% to 12% by the end of this decade. Excluding the probably constant share of hydropower (4%) this means a four-fold increase of the share of essentially wind, solar and biomass generated power.[6]

In addition, the overall energy import dependence of the (enlarged) European Union is expected to increase from the current 50% to 70%.[6] While growing import dependence is not necessarily a threat to security supply as such, it certainly will increase the interest for alternatives with the potential to alter this trend.

III. Objectives

While large-scale terrestrial or space solar power plants are not expected to play any significant role in the energy system within the next 20 years, the next large energy discussion after the current one is likely to take place around 2020/30.

Given the long technology maturation times as well as the long life-cycles of power plants and the intermediate nature of the concept: too advanced for mainstream programs but also too attractive as a long-term solution for a range of energy related problems to be neglected, one of the long-term objectives of the current SPS Programme Plan is to advance the concepts in order to reach a decision-enabling maturity level.

Having acknowledged the fact that there are no principal technical “show-stoppers”, that conceptual and technological progress has reduced the required orbital masses significantly and gradually over the last 30 years (and that there is little reason to believe that this trend is changing soon), the first objective was to assess the general viability of the concepts.

While such assessments have been undertaken in the past, none of them seems to have been able to convince a larger audience than the inner SPS research community. For the credibility and impact of the validation phase results, the studies were therefore lead by independent energy consultants.

A. Boundary Conditions

The general frame for the validation phase was fixed by:

- limitation to the wider European context;
- comparison with terrestrial solar power systems;
- assessment of energy payback times;
- comparison of technologies at same technology maturity levels;
- integration into realistic projections of European energy demand patterns in 2025/30.

The limitation to only European scenarios (with a wide interpretation of Europe) imposes some severe restrictions since most of the past SPS scenarios were designed to be inherently global. This restriction was important in order to include the concepts into a 2025/30 European electricity system with realistic demand profiles.

The restriction of the comparison to only solar power systems makes the comparison easier and fairer but also implies that very large scenarios are less realistic for the terrestrial option (e.g. solar power systems supplying more than 50% of the total European demand).

Given that one of the regular critics is related to alledged unreasonably high energy pay-back times (for terrestrial as much as for space systems), their thorough assessment was an integral part of the comparison. It is furthermore important to notice that the comparison was based on actual component material energy costs (contrary to the easier but less accurate cost-energy relationship).

B. Integration: space and terrestrial plants

Given the different levels of technology maturity for space and terrestrial solar power concepts and the high share of the storage costs for terrestrial base-load systems, the possible mutual advantages of an integration of space and terrestrial solar power plants were assessed.

IV. EUROPEAN APPROACH --- METHODOLOGY

A. European Network on Solar Power from Space

The first step was taken in August 2002 with the creation of the European Network on Solar Power from Space.[2,3] It provides a forum for all relevant and interested European players in the field of SPS, including industry, academia and institutions.

After the definition of the main aspects of the SPS Programme Plan with its three phases as described in [2], the activities were done in parallel ESA-internally within studies by the Advanced Concepts Team and by European industrial and academic contractors.[2,7,8,9,10]

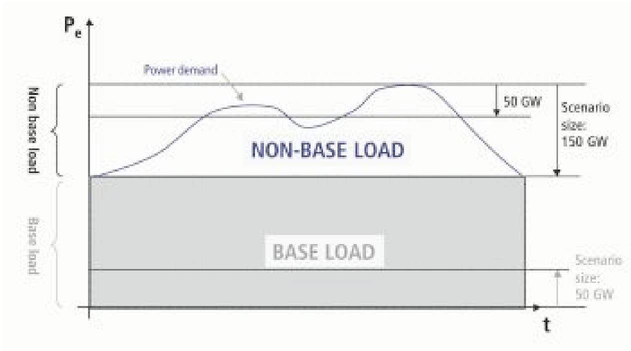

Figure 2: Definition of base and peak-load (non-baseload) power as used for the present assessment.

B. Integration of Terrestrial Solar Power Expertise

Two parallel industrial studies were undertaken. The two consortia were led by independent energy consultant companies, which coordinated the space as well as terrestrial solar power expertise.

C. Power Consumption Profile

The scenarios were divided into the provision of base-load power and the provision of peak-load power. For this purpose, base-load power was defined as the constant provision of the lowest daily demand level. Peak load power was then defined as “non-base-load” power as shown in Fig. 2, which also gives the typical daily power lead profile for Europe.

D. Supply Scenarios

Solar power satellites are frequently proposed in the multi-GW region, while terrestrial plants are currently proposed in the several MW region. In order to derive the scaling factors for space and terrestrial solar power plants, different plant sizes ranging from 500 MW_e to 150 GW_e and 500 GW_e for the peak-load and base-load scenarios respectively have been analysed.

E. Launch Costs

Launch costs are the single most important parameter in assessing the economic viability of solar power satellites. The assumption of fixed launch costs would predetermine the outcome of system comparison studies.

As a consequence, launch costs were treated as open parameters for the present assessments between boundaries given by the current launch cost as upper and the fuel costs as lower limit.

In order to overcome the “chicken-egg” problem of: the launch frequency required by the construction of SPS reduces the launch costs to values required for the economic construction and operation of SPS, a “learning curve approach” was agreed upon by both consortia. Starting from current launch costs, a 20% reduction was assumed by each doubling of the total launch mass. (progress rate of 0.8)

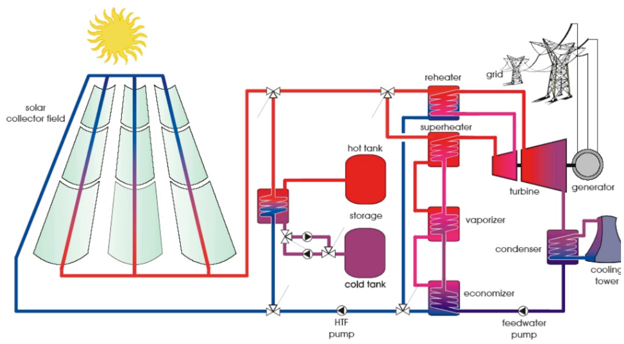

Figure 3: Outline of a terrestrial solar trough plant

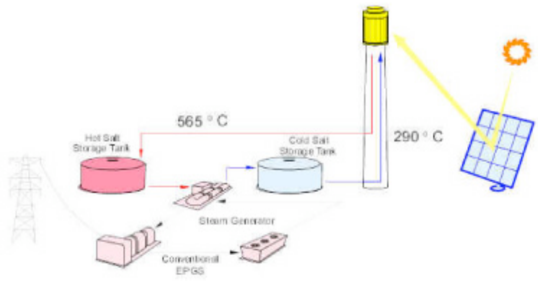

Figure 4: Outline of a terrestrial solar tower plant

In a first step, space and terrestrial plants were compared by excluding launch costs. This comparison and the total cost difference were then taken to determine the maximum allowed launch costs for the space scenario in order to be competitive with terrestrial plants.

In a third step, the progress rate was used to determine the reduction of the launch costs due to the launches of SPS components for all scenarios. This value was then compared to the required value to become competitive for a certain scenario as determined in step two. The approach did not take into account potential multiplication factors due to the opening of additional markets created by lower launch costs.

V. Reference Systems - Terrestrial

For the base-load power supply scenario, one consortium opted as most likely system for a system of multiple 220 MW_e solar thermal tower units distributed within the south European sunbelt region (including Turkey). The other consortium based the analysis on a solar thermal trough system installed in an unpopulated area in Egypt. Both consortia considered PV plants as higher-cost alternatives with current technology but with large cost reduction potential for the 2020/30 timeframe.

The system of choice for the peak load power supply of one consortium was a highly distributed PV-based scenario, where the amount of unused, potentially available and usable building surfaces were taken into consideration. The other one opted for the same design as for the base-load solar power plant.

For a detailed description of the solar thermal and terrestrial PV technologies, it is referred to [11-19].

A. PV System Technology

The assumptions of for 2025/30 PV technology are a 20% PV module efficiency based on a 3rd generation multi-junction cell. The state of the art turn-key total investment costs are assumed at 4 500 €/kW_p at a current total capacity of 2 GW_p. The cost calculations for the 2025/30 scenarios for terrestrial as well as for space based PV power plants were based on a 20% cost reduction by each production doubling (which corresponds to the trend of the last decade) until the total installed capacity reaches 500 GW_p when the reduction per each doubling was assumed to be only 8%.

A total plant life-time of 25 years with operations and maintenance costs of about 2-3% were taken as basis.

B. Solar Thermal Technology

Solar thermal technology for electric power plants is more mature than PV technology for power plants and under certain conditions already competitive to traditional fossil fuel based plants.[14,13] This is valid for solar thermal trough plants as well as for solar tower plants. The schematic layouts of a solar thermal trough and tower plants are shown in Fig. 3 and Fig. 4.

A state-of-the-art cost of 225 €/m^2 of effective trough collector area have been assumed with additional 800 €/kW_e for the power block and 30 €/kWh_{th} for the thermal storage. For the 2025/30 scenario, a progress rate of 0.88 was assumed (12% decrease per each doubling of installed capacity), changing to 0.96 after installation of 500 million m^2 of effective collector area. (2004: about 2.3 million m^2)

The baseline for solar thermal tower plants was an unit size of 220 MW_e covering an area of 14 km^2 with a capacity factor of 73%. The current levelized electricity costs (LEC) of 0.042 €/kWh_e are expected to fall to 0.03 €/kWh_e by 2025/30.

C. Storage Systems

The Egypt based solar thermal trough plant concept relies on the availability of adapted local terrain features for the implementation of a pumped hydrostorage system.

The distributed solar thermal tower scenario uses local compressed hydrogen storage units as a baseline (pumped hydrostorage was considered as an alternative in case of appropriate local terrain).

State of the art pumped hydrostorage plants (1 GW, 6 GWh, discharge efficiency of 75%) present an investment cost of about 14 €/kWh + 700 €/kW that is assumed to decrease by 15% to approximately 12 €/kWh + 600 €/kW with operation costs of 4 €/MWh until 2025 (4 GW, 24 GWh, discharge efficiency of 85%).[20]

In case of the hydrogen storage system for 2025, investment costs of the electrolyzer are assumed to be 500 €/kW of power of produced hydrogen, corresponding operation and maintenance costs of 1.5% of the overall investment costs. For the pressure storage vessel 1.92 million € are estimated per each unit. Finally, for the re-conversion equipment, 500 €/kW_e of investment costs and 0.01 € per produced kWh_e are assumed.

D. Transmission Systems

The scenario based on a central large terrestrial solar trough plant in Egypt relies on relatively long power transmission lines. The chosen technology were high voltage direct current (HVDC) lines with a capacity of 5 GW_e per line as of today and an expected increase to 6.5 GW_e by 2025/30. This also reduces the total cost from today 60 M€/(1000 km·1 GW) to 46 M€/(1000 km·1 GW) with constant per-station costs for the required DC-AC converter stations of 350 M€ each. Operations and maintenance were taken into account at 1% of the total investment costs.

The scenario based on distributed solar tower plants across the European sunbelt does not require significant additional transmission capacity for scenarios up to 100 GW_e above which the concepts rely on the HVDC current technology.

VI. Reference Systems - Space

Given the restriction to European scenarios, only geostationary space systems were taken into account. While one consortium has opted for wireless power transmission by laser, the other preferred the 5.8 GHz microwave wavelength. Both concepts rely on land-based terrestrial receiver sites (instead of sea-based receivers).

In principal, the first phase was not intended to develop new space solar power station designs, but to rely on the most advanced technical concepts proposed. (European Sailtower concept, the concepts proposed during the NASA Fresh Look and follow-on studies as well as Japanese concepts)[21,22,23]

Due to limited data on concepts relying on laser power transmission, some further assumptions have been made. The general outline of the laser-based space plant is a geostationary space units with 111 km^2 of thin film PV cells augmented by concentrators of the same area. The 20% efficient system generates 53 GW_e in orbit, feed into a 50% efficient IR-laser generation system at 1.06 µm transmitted with average losses of about 38% essentially due to beam shaping and atmospheric attenuation to an almost 70 km^2 large PV reception site in North Africa. The ground PV system would have a 20% efficiency for direct sunlight but a 52% conversion efficiency for the IR-laser beam. Adding additional 4% collection losses in space and 4% losses on ground, the space segment would deliver a constant supply of 7.9 GW_e to the terrestrial power grid.

VII. Comparison Results

A. *Base-load Power Supply*

In the case of base-load scenarios, terrestrial solar tower plants with local hydrogen storage capacities promise electricity generation costs between 9 €cent/kWh for the smallest (500 MW_e) and 7.6 €cent/kWh for the largest (500 GW_e) plants.

Under those conditions, solar power satellites would not be competitive with the smallest scenarios even at zero launch costs. For the 5 GW_e and larger scenarios, launch costs between 620 and 770 €/kg are required for SPS to be competitive with terrestrial plants. In case local pumped hydrostorage facilities are available, the required launch costs would be significantly lower, dropping to roughly one third of these values. (Tab. 2)

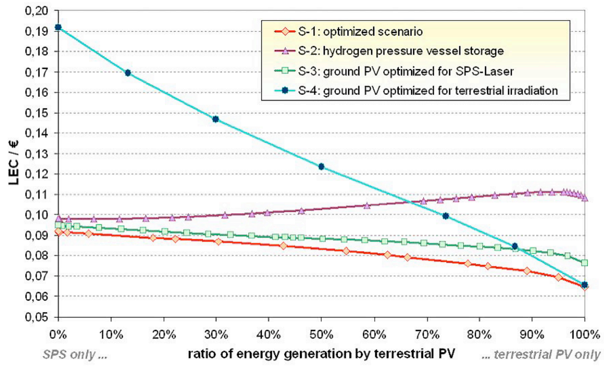

Figure 5: Comparison of different scenario combinations of space and terrestrial solar power plants

For the comparison of laser-based space systems with terrestrial systems in North Africa the space and ground systems are more integrated and cannot be discussed and compared completely separately since the ground site is used at the same time as receiving site for the space system and as (independent) terrestrial solar power plant based on direct solar irradiation.

With 530 €/kg into LEO launch costs, base-load power supply scenarios by space-based systems for 10, 25, 50, 100 and 150 GW_e scenarios were compared with terrestrial-only concepts located in North-Africa. The total LEC for the space scenario range from 0.26 €/kWh for the smallest to 0.10 €/kWh for the 150 GW_e concept. The summary parameters of the system are listed in Tab. 1.

For the combined system (the integration of space and terrestrial solar plants) the range of (terrestrial) technology options imposed the reduction of the analysis to distinctive scenarios. Within each scenario, the levelized electricity costs were calculated for the entire range: from power from space only to no additional power from space. The design of the ground receiver changes in type, spacing and inclination depending whether it should be optimized as ground system for the space segment or as pure terrestrial solar plant.

The four scenarios assessed in detail were

- central PV receiver optimized for laser beam, additional PV optimized for solar irradiation; pumped hydroelectric storage (Scenario S-1);
- central PV receiver optimized for laser beam, additional PV optimized for solar irradiation; hydrogen pressure vessel storage (Scenario S-2);
- entire PV receiver optimized for laser beam; pumped hydroelectric storage (Scenario S-3);
- entire PV receiver optimized for solar irradiation; pumped hydroelectric storage (Scenario S-4).

The results of the combination in terms of levelized electricity generation costs for the entire range from all-space to no-space extremes for each of the four scenarios are displayed in Fig. 5. It can be seen that given the uncertainty inherent in 20-year forecasts, the LEC for the different scenarios (except the one optimized for converting only direct solar irradiation; S-1) are very close to each other and not changing dramatically by changing the percentage of space to ground supplies.

TABLE 1
SPACE SYSTEM PARAMETERS - LASER POWER TRANSMISSION

Demand	GW	10	25	50	100
units (space/ground)		1/1	3/1	6/2	12/4
space PV cap.	GWp	22,1	66.4	133	266
terr. PV cap.	GWp	36653	36653	17	33.9
stor. cap.		200	500	1000	2000
LEC	€/kWh	0.26	0.166	0.137	0.113
EPT	months	4.2	3.7	3.7	3.7

TABLE 2
COMPARISON: BASE-LOAD SCENARIOS
SPACE (RF POWER TRANSMISSION)–TERRESTRIAL (SOLAR TOWER)
PUMPED HYDROGEN OPTION IN BRACKETS

Total Power Supply	**Concept**	**electricity generation cost**	**permitted launch costs**
GWe		€/kWh	€/kg (LEO)
	terrestrial	0.090 (0.059)	
0.5	space	0.280 (0.280)	-
	terrestrial	0.082 (0.053)	
5	space	0.044 (0.044)	750 (200)
	terrestrial	0.080 (0.051)	
10	space	0.047 (0.046)	620 (90)
	terrestrial	0.076 (0.049)	
50	space	0.035 (0.034)	770 (270)
	terrestrial	0.075 (0.047)	
100	space	0.034 (0.033)	770 (250)
	terrestrial	0.076 (0.050)	
500	space	0.039 (0.039)	670 (210)

TABLE 3
COMPARISON: PEAK-LOAD SCENARIOS
SPACE (RF POWER TRANSMISSION)–TERRESTRIAL (SOLAR TOWER)
PUMPED HYDROGEN OPTION IN BRACKETS

Total power supplied	Concept	Generation cost	Required launch cost
GWe		€/kWh	(€/kg)
0.5	terrestrial	10.6 (10.2)	
	space	441	-
5	terrestrial	7.6 (6.6)	
	space	36	-
10	terrestrial	5.3 (4.0)	
	space	19	-
50	terrestrial	1.09 (0.7)	
	space	0.871	155 (-)
100	terrestrial	0.673 (0.48)	
	space	0.246 (0.245)	958 (540)
150	terrestrial	0.532 (0.280)	
	space	0.131 (0.130)	1615 (605)

As general tendency, the importance influence of the availability of cheap local storage is confirmed by these curves: where (cheap) pumped hydroelectric storage is possible due to terrain specifics, terrestrial plants are generally producing cheaper electricity than space plants, even if the ground station is optimized for the space segment. This tendency has to be taken with some care however, since the reduction from an *all space* to an *all terrestrial* case is only about 1 €cent. The results are based on launch costs of 530 €/kg.

Over all ranges the most advantageous scenario is scenario S-1, with a terrestrial receiver containing a central part optimized for converting the laser from the SPS and the surrounding photovoltaics optimized for direct solar irradiation. In case pumped hydroelectric storage is available, the *all terrestrial* solution prevails over the all space solution by close to 3 €cent/kWh. In case hydrogen storage is required, the *all space* option is little more than 1 €cent/kWh cheaper than the *all terrestrial* scenario. Since both of these curves have their minimum on the (opposite) extremes, a combination of both will have a local minimum somewhere close to a scenario with 20% space and 80% terrestrial supply.

With lower launch costs, this local minimum will shift towards the right side of Fig. 5, the *all terrestrial* option and inversely will tend towards a higher percentage of the overall power delivered from space (left side of x-axis).

B. Non base-load Power Supply

For non-base-load scenarios, solar tower plants with local hydrogen storage capacities have generation costs between 10 €/kWh for the smallest scenarios to 53 €cent/kWh for the largest (150 GW_e) plants. Solar power satellites reach potentially competitive electricity generation costs only above relatively large plant sizes of about 50 GW_e.

For the 50 GW_e and higher scenarios, launch costs between 155 and 1615 €/kg would be required for SPS to reach a competitive level to terrestrial plants. In case local pumped hydrostorage facilities are available, the required launch costs would be lowered by about a factor two. (Tab. 3)

C. Energy payback times - primary validity

Space as well as terrestrial solar power plant concepts have been "accused" of violating the fundamental law of every power plant: generating more energy than necessary for their proper construction. It was therefore important to assess the exact cumulated energy demand (CED) of the systems and compare it with the energy output over their lifetime. The resulting energy payback time provides a measure for the validity of the concepts as power plants.

There are several methods to assess the cumulated energy demand of any system. The fasted but also most imprecise method is an energetical input/output analysis. This method was already partially applied to SPS systems in the past, in part based on energy estimates derived from material costs, assuming a reliable €-Joule relationship. In case all the components are known a material balance analysis can be made, combining the mass of all single components with its specific energy demands obtained from specialized databases.

The present analysis relies on a complete material flow analysis, the most precise method to determine the CED. For some parts of the space system for which the data for the exact material flow analysis were not available, the method of material balance was used, partially based on CEDs provided by specialized databases.

In all considered cases, the energy payback times for space and terrestrial solar power plants were lower or equal to one year. For the Egypt-based terrestrial system, the energy payback times seem to be slightly higher than for the distributed system in the European solar belt. In both cases, from a purely energetic point, solar power satellites promise a slightly shorter energy payback time, ranging depending on the size and the concept (all including the launchers) from 4 month to 2 years.

It should be noted that while using slightly different methods and different space concepts, the assessments for the space segments derive almost exactly the same values (3.9 to 4.8 months) despite their different transmission technologies. The terrestrial scenario based on solar thermal tower plants (local hydrogen storage) in south Europe leads to energy payback times of 8.4 months, the solar thermal trough case (with pumped hydroelectric storage) in North Africa has a calculated payback time of 8.1 to 8.9 months. The energy payback times for the terrestrial photovoltaic case in north Africa are expected to fall from about 31 months with advanced current technology to 8.3 months based on 2030 PV technology.

The detailed assessments have shown that both, space and terrestrial solar plants have extremely short energy payback times and are from a purely energetic point of view attractive power generators.

VIII. CONCLUSIONS

In an attempt to contribute to the discussion on the most appropriate options for a sustainable energy system for the 21st century, solar power from space concepts were compared with terrestrial solar power plants in the timeframe until 2030 on equal technology assumptions.

While terrestrial solar power plants are expected to contribute significantly to the European electricity production in the next 20 years, solar power satellites are expected to reach their technical and economic maturation phase only at the end of the considered timeframe.

The competitiveness of the space option increases with increasing total plant sizes. Under the given assumptions, space options are competitive with terrestrial plants only for relatively large solar power plants (depending on the type from 0.5 to 50 GW_e).

Earth-to-orbit transportation is the single most important factor requiring a decrease of more than one order of magnitude compared to current launch costs. Depending on the plant size, launch costs between 155 and 1615 €/kg_{LEO} for peak-load and around 600-700 €/kg_{LEO} for base-load supply scenarios are necessary to be competitive with terrestrial solar power plants.

The advantage of combined space and terrestrial solar plants based on laser power transmission depends on the available terrestrial storage facilities, especially appropriate terrain for large pumped hydroelectric storage.

Both, space and large terrestrial solar power plants have very attractive, low energy payback times. Almost all space and terrestrial concepts produce within less than one year more energy than was needed to produce and operate them, based on a detailed complete material flow analysis.

Based on the obtained results, solar power from space confirms its potential as attractive option for a sustainable energy system, requiring significant technology maturation and further investigations into the most likely first steps, their integration into then existing terrestrial solar power plants.

TABLE 4
COMPARISON: ENERGY PAYBACK TIMES

Total Power Supply GWe	Concept	energy payback time Months
0.5	SOT1 (H2)	8.4
	SOT2 (pumped)	7.7
	PV (pumped)	8.2
	SPS laser	-
	SPS μ-wave	24
5	SOT1 (H2)	8.4
	SOT2 (pumped)	8.3
	PV (pumped)	9.2
	SPS laser	-
	SPS μ-wave	4.8
10	SOT1 (H2)	8.4
	SOT2 (pumped)	8.9
	PV (pumped)	8.2
	SPS laser	4.4
	SPS μ-wave	4.8
100	SOT1 (H2)	8.4
	SOT2 (pumped)	8.1
	PV (pumped)	8.3
	SPS laser	3.9
	SPS μ-wave	4.8
150	SOT1 (H2)	8.4
	SOT2 (pumped)	8.2
	PV (pumped)	8.5
	SPS laser	-
	SPS μ-wave	4.8

SOT1: South European Solar Tower case
SOT2: North African Solar Trough case
PV: North African Solar Photovoltaic case

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