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ROLES OF SOLAR POWER FROM SPACE FOR EUROPE: SPACE EXPLORATION AND COMBINATIONS WITH TERRESTRIAL SOLAR POWER PLANT CONCEPTS

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The paper presents the prospective roles of SPS concepts for Europe, shows the outcome of the studies undertaken by ESA during the first phase of the European SPS Programme Plan and gives insight into the planned activities. These studies, performed by European industry and research centres in close cooperation with the ESA Advanced Concepts Team, were all directed towards the main goal of the first phase, the assessment of the principal validity and viability of solar power from space concepts in the light of advances in alternative sustainable, clean and potentially abundant solar based terrestrial concepts, taking into account expected changes in the European energy system (e.g. gradual introduction of hydrogen as energy vector).

Special emphasis is given to the possibilities of integrating space and terrestrial solar plants. Depending on the timescale and geographic location considered, solar thermal options or solar photovoltaic options are more advantageous, the benefits of the later getting more attractive the further in the future the comparison and the greater the distance to the geographic equator.

Laser and microwave power transmission is considered. While laser power transmission offer fundamental advantages for the integration into terrestrial solar power plants, the availability of existing ground receptions, power management and power distribution systems are also beneficial to the economics of the more efficient microwave systems.

The relative proximity of good locations in the Sahara desert to the large European energy consumer market puts Europe in a special position regarding the integration of space and terrestrial solar power concepts. The papers presents a method to optimise such an integration, taking into account different possible orbital constellations, terrestrial locations, plant number and sizes as well as consumer profiles and extends the scope from the European-only to a multi continental approach including the fast growing Chinese electricity market.

This work intends to contribute to the discussion on long-term options for the European commitment to durable CO_2 emission reduction, which probably requires substantial changes in our energy system. Cleaner electricity generation and environmentally neutral transport fuels (e.g. solar generated hydrogen) are two major tools to reach this goal.

I. INTRODUCTION

ESA has started in 2002 in the frame of its Advanced Concepts Team a multiyear programme related to SPS. The programme is divided into three phases.[2] The outcome of the first phase, the "General Viability Phase" will be presented in this paper.[3]

A. Objectives

Solar power satellites receive renewed attention by a larger audience in a cyclic manner. The reason for this pattern might be the intermediate nature of the concept: too advanced for mainstream programmes but also too attractive as a long term solution for a range of energy related problems to be neglected.

ESA's activities have to be seen against this background. Having acknowledged the fact that there are no principal technical "show-stoppers", that conceptual and technological progress has reduced the total orbital masses significantly and gradually over the last 30 years (and little reason to believe that this trend is changing soon), the first objective was to assess the larger general viability of the concepts.

While such assessments have been undertaken in the past, most of them were based on either a comparison of only final $€/kWh$ electricity generation costs, or done from an SPS perspective without experts from other energy systems (and thus sometimes based on different technology maturity levels).

The overall analysis was divided into two main categories:

1. Space-to-Earth energy systems (classic SPS concepts)
2. Space-to-Space energy systems (for space exploration and utilisation)

For the Space-to-Earth category, the classic application of SPS concepts as introduced by Peter Glaser in 1968[1], the general frame for the validation phase was fixed by:

1. limitation to the wider continental European context;
2. comparison only with comparable terrestrial solar power systems;
3. inclusion of a comparison of energy payback times;
4. comparison of technologies at same technology maturity levels;
5. 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 felt important to include such stations 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 demand).

Given that one of the regular critics is related to perceived 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).

1. 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.

2. In-space applications

For the space-to-space category, the assessment was limited to three classes of applications:

1. Earth orbit applications;
2. Lunar and Martian surface applications;
3. interplanetary spacecraft.

For each of the classes, one or two typical missions were taken as basis. The main validation criteria was the total mass for similar power levels available at the receiving spacecraft. The alternatives for all three cases are either solar panels at the level of the spacecraft or, in the case of surface missions and interplanetary spacecraft, nuclear power sources.

B. Motivation

The motivation for the SPS programme plan can be divided into a global dimension and a European dimension for space to Earth option studies.

1. Global Dimension

On a global, long-term scale, there are three mayor parameters that have to be considered in connection with the energy system for the 21^{st} 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 degree, 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 in the most populated and fasted increasing parts of the world, in Africa and Southeast-Asia respectively.[4]

Therefore, if the natural increase of the total power consumption due to population development should be accompanied by an increase of average level standards in developing parts of the world, 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 billion tons per year from currently 16 billion 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-demanding 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.

While solar power from space certainly is not *the* solution, it constitutes an attractive option: it is almost entirely free of GHG emissions, available at very large scales and potentially at any place on the globe and it is possible to be integrated into a hydrogen based economy.

2. European Dimension

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 system.[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.[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 this trend.

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, one of the long-term objectives of the current SPS Programme Plan is to prepare the topic in order to be at a maturity level which will allow it to be taken into account for this next round of larger debates on future energy systems.

3. Space Dimension

With current technology, a range of space missions is not feasible without the use of nuclear power sources. In addition to outer solar system missions beyond the orbit of Jupiter where the intensity of solar irradiation is too low for reasonably sized solar panel powered spacecraft, several planetary and lunar surface missions also rely on nuclear power sources (e.g. all past successful Martian surface missions used at least radioisotope heating units or radioisotope thermoelectric generators). For the result of these activities we refer to [7].

II. EUROPEAN APPROACH — METHODOLOGY

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, 8, 9, 10, 11]

Given the importance of the European terrestrial solar energy research community, the scope of the validity phase and the relatively restricted size of the European SPS community, the involvement of experts on terrestrial solar power applications and the larger European energy sector was necessary for the space-to-Earth industrial assessment studies.

Two parallel industrial studies were undertaken. The two consortia were led by independent energy consultant companies and regrouped space as well as terrestrial solar power expertise in form of subcontractors.

Two technical workshops accompanied the studies, ensuring the same basic underlying assumptions and technology maturity levels of system and subsystem technologies.

For the space to Earth scenarios, the focus was not on the development of new designs for space systems, but emphasis was given to the integration of the most recent and up-to-date designs available into the comparison models. In the case of large scale terrestrial solar power plants, reasonable upscaling of currently operating plants was possible by taking into account the assumed technology progress.

A. Power Consumption Profile

The power need scenario was 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 figure 1, which also gives the typical daily power lead profile for Europe.

B. 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 considered.

C. Treatment of 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)

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 a multiplication factor due to the opening of additional markets created by lower launch costs.

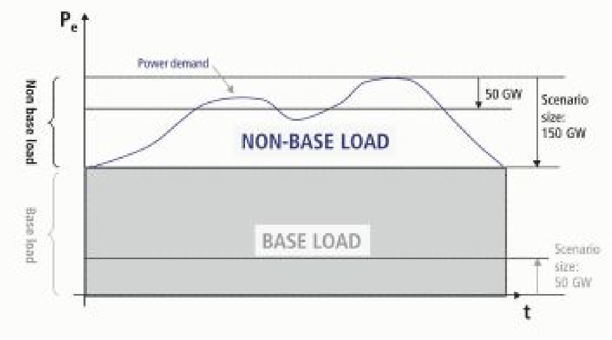

FIG. 1: Definition of base-load and peak-load power.

III. REFERENCE SYSTEMS

A. Terrestrial Solar Power Plants

The two consortia have chosen different terrestrial reference systems for the basis of their comparison. For the base-load power supply scenario, one consortium opted for a system of multiple 250 MW_e solar thermal tower units distributed within the south European sunbelt region including Turkey, the other consortium based their analysis on a solar thermal trough system installed in an non-populated area in Egypt. PV plants were considered by both consortia as higher cost alternatives.

The system of choice for the comparison done by one consortia for the peak load power supply was a highly distributed PV based scenario, where the amount of unused, potentially available and usable building surfaces were taken into consideration.

For a detailed description of the solar thermal and terrestrial PV technologies, we refer to [12, 13, 14, 15, 16, 17, 18, 19, 20].

1. PV System Technology

The assumptions of for 2025/30 PV technology are a 20% PV module efficiency based on a 3^{rd} generation multi-junction cell. The state of the art turn-key total investment costs are assumed at 4500 $€/kW_p$

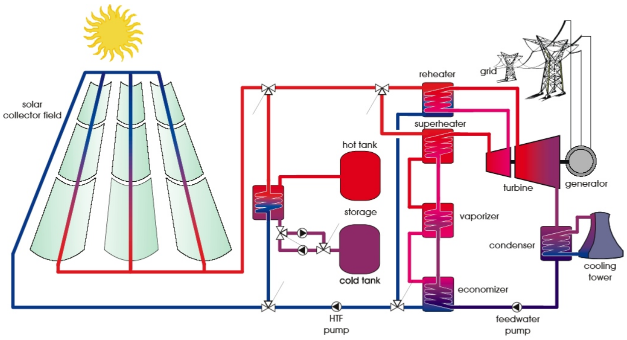

FIG. 2: Schematic representation of a solar thermal trough plant.

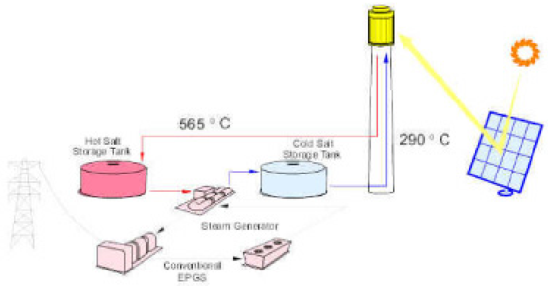

FIG. 3: Schematic representation of a solar thermal tower plant.

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.

2. *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, 15] 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 figure 2 and figure 3.

A state of the art costs 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.

3. *Storage Systems*

The Egypt based solar thermal trough plant relied 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 $€/MWh$ (4 GW, 24 GWh, discharge efficiency of 85%).[21]

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 in vestment costs and 0.01 € per produced kWh_e are assumed.

4. *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 $M€/(1000\,km \cdot 1\,GW)$ to 46 M€$/(1000\,km \cdot 1\,GW)$ with a constant cost 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 in 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.

B. Space Solar Power Plant

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

No new space solar power segments were developed in the frame of the first phase of the SPS Programme Plan, but the analysis relied on technical assumptions of the European Sailtower concept, the concepts proposed during the NASA Fresh Look and follow-on studies as well as Japanese concepts.[22, 23, 24]

IV. 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 and 7.6 €cent/kWh for the smallest (500 MW_e) and the largest (500 GW_e) plants respectively. Solar power satellites are not competitive with the lower scenarios even at zero launch costs.

For the 5 GW_e and higher 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 with roughly one third of these values.(Table I)

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 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.(Table II)

TABLE I: Comparison of base-load supply scenarios with RF based space systems and distributed terrestrial solar tower plants. (pumped hydro-storage option scenarios in brackets)

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

TABLE II: Comparison of peak-load supply scenarios with RF based space systems and distributed terrestrial solar tower plants. (pumped hydro-storage option scenarios in brackets)

Total Power Supply GW_e	**Concept**	**electricity generation cost** €/kWh	**permitted launch cost** €/kg (LEO)
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)

C. Comparison of Energy payback times

Given the high uncertainty inherent to some of the system aspects, a comparison of space and terrestrial plants based on only physics parameters was done.

Contrary to past work, energy values were calculated without using an assumed €-Joule connection, but taking as a basis energy intensities for subsystem components and materials (specialised databases).

For all regarded 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.

V. *GLOBALISATION* OF RESULTS

The assessment of the first phase was deliberately limited to European scenarios and did not take into account potential global dimensions. Space activities however are inherently global and the ability of space segments to supply power to multiple distant ground segments has not been taken into account yet.

An internal assessment together with the University Politecnico di Milano (I) investigates ways of combining space segments with multiple ground stations. The number of variables, especially the orbital parameters and the location of the ground station (and the associated local solar irradiation profile and distance to consumer centres) calls for a global optimisation approach.

In order to overcome one of the drawbacks of assessments targeting only global scenarios, their non-integration into actual consumer profiles, the model was first designed to supply only two plants supplying the two specific consumption profiles of Europe and China, the currently fastest growing electricity market.

A. System Model

For a preliminary analysis of a combined terrestrial-space power system we implemented a simplified model made of two parts.

The terrestrial segment is modelled as two extended solar array fixed on the surface of the Earth and with normal of the array surface aligned with the local normal vector.

The longitude and latitude coordinate of the two ground installations λ_1, θ_1 and λ_2, θ_2 are free to vary in a limited domain corresponding to the Sahara desert and to the Gobi desert respectively for Europe and China. A limit of 10 degrees on the minimum elevation angle is included.

The orbit of the space segment is propagated analytically without considering any orbit perturbation. The five parameters $(a, e, i, \omega, \Omega)$ of the orbit are left free to vary in a given range. The SPS is modelled as a point mass to which the surface As of an equivalent extended solar array is associated. The surface is used to compute the total power generated and total dry mass of the spacecraft considering a solar array with a mass ratio of 0.5 kg/W.

The normal to the SPS array surface is aligned with the normal to the osculating orbital plane and no model for attitude or solar array orientation is implemented. The power beam has a steering cone of 30 degrees and the power transmission is off during eclipses.

In addition the propellant weight required to transfer the SPS from a 200 km circular orbit to the operative orbit is considered plus the mass of the tanks computed as 10% of the mass of the propellant. In order to take into account the effects of orbit perturbations on the pericentre anomaly and on the ascending node, an additional propellant mass for orbit maintenance is added to the overall mass of the space segment. Orbit perturbations are estimated taking into account just the effects of J2.

On Earth the model for power storage is obtained by simply computing the exceed power times the time step (1 hour) times an efficiency that takes into account the total power loss from the produced power to the used power (currently assumed at about 60%). The total power loads for Europe and China are given in terms of tabulated data and were interpolated on the required time span.

B. Multi-objective Optimisation

The problem can be stated as follows:

$$\min_{x \in D} F(x) = \begin{cases} f_1(x) = \text{stored energy} \\ f_2(x) = \text{SPS mass in orbit} \end{cases} \tag{1}$$

subject to the constraint

$$P_{out} \geq P_{load}, \tag{2}$$

where the P_{out} is the instantaneous power delivered by the combined terrestrial-space system including store and P_{load} is the power required.

This is a multi-objective optimisation problem with a number of possible solutions. The way this can be effectively solved is to use a global evolutionary approach that is able to generate a good part of the Pareto set. The Pareto set is made of all non-dominated pairs of $[f_1, f_2]$, where a non-dominated pair is such that no other pair is better in both f_1 and f_2. In this paper the problem is solved with a Matlab tool developed for global optimisation (EPIC

— Evolutionary Programming and Interval Computation) that was extended to treat multi-objective problems.

The first results have demonstrated the principal applicability of the method to this problem. Further investigations are ongoing.

VI. CONCLUSIONS

The overall conclusions of the first phase of the SPS Programme plan can be summarized with several points.

While terrestrial solar power plants will already play an increasing part in European electricity production in the next 20 years, solar power satellites are technically and economically not mature enough to play any role within the timeframe studied until 2025.

The competitivity of the space option increases with increasing total plant sizes. Under the given assumptions, space options are not competitive with terrestrial plants for relatively small solar power plants, depending on the type from 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 combination of space and terrestrial solar plants, where the terrestrial plant is converting laser power from the space segment in addition to solar power provides no economic advantage in terms of levelized electricity costs over terrestrial only solutions.

The extension of combined systems to worldwide scenarios with globally distributed ground stations is complex if realistic consumption profiles are taken into account. Global optimisation methods are currently studied for these cases, starting with first only two ground stations, delivering Europe and China.

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