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PROSPECTS FOR SPACE SOLAR POWER IN EUROPE

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In 2002, a phased, multi-year approach to space solar power has been published. Following this plan, several activities have matured the concept and technology further in the following years. Despite substantial advances in key technologies, space solar power remains still at the weak intersections between the space sector and the energy sector.

In the 10 years since the development of the European SPS Programme Plan, both, the space and the energy sectors have undergone substantial changes and many key enabling technologies for space solar power have advanced significantly. The present paper attempts to take account of these changes in view to assess how they influence the prospect for space solar power work for Europe.

I INTRODUCTION

The concept of generating solar power in space and transmitting it to Earth to contribute to terrestrial energy systems has received period attention since P. Glaser published the first engineering approach to it in 1968 [1]. Considerable efforts were spent on the concept during a joint DoE/NASA effort from 1977 to 1980 [2]-[6] and again from 1995 to 2000 during the NASA Fresh Look study on SPS [7]-[9]. Since the 1980s, Japanese researchers have conducted key experiments, especially at the universities of Kobe, Kyoto and Tokyo.[10][11][12] In Europe, some conceptual work has been done at national as well as European level on the topic.[13][14] In 2002, a new, three-phase programme on SPS has been presented at the second World Space Congress [15].

I.1 Scope

The purpose of the present paper is to take account of the results of the European SPS programme plan as published in 2002 and to propose an updated approach based on an analysis of the technological and programmatic changes occurred since 2002.

II EUROPEAN SPS PROGRAMME PLAN

The SPS Programme Plan has been published in 2002 in order to provide a structuring frame for a number of mainly isolated activities more or less loosely connected to advancing the general concept of space solar power in Europe [15]. It took advantage of the recently published work done in the frame of the NASA Fresh Look Study as well as the work on a European sail tower concept by Klimke and Seboldt [16], [17].

Based on these results, which re-confirmed the principal technical viability of space solar power concepts, the focus of the first phase of the European SPS programme plan has been to enlarge the evaluation scope of space solar power by including expertise from the non-space sector and comparing space-based solar power plant options with comparable terrestrial alternatives. The comparison was based on commonly agreed expectations for technology readiness levels for systems ready to be deployed in 2025, excluding assumptions on launch costs, which were treated as an open parameter. The overall scope of the assessment was furthermore limited to Europe, defined as Europe and its immediate geographic vicinity, thus including North Africa and the Middle East. This first general validation phase, thus included

- two studies focussed on the comparison of space and terrestrial solar power options, [18] [19]
- one study on the validity of space solar power and wireless power transmission for space exploration (Moon, Mars, deep space and Earth Orbits), [20]

as well as four small accompanying studies aimed at identifying potential showstoppers and addressing in particular:

- legal aspects of space solar power concepts [21];
- options for non-mechanical laser beam steering for wireless power transmission applications [22];

- potential atmospheric effects of high power microwave densities in different atmospheric layers [23];
- a computerised model for space solar power concepts [24].

The results of the validation phase studies were presented to the international community at the 4th international conference on solar power from space in Granada, Spain in June 2004, followed by a peer review of the results by Japanese researchers [25].

The second phase of the SPS programme plan, aimed at maturing some key technologies further, with an attempt to be complementary to other international activities on SPS. Specifically, the key SPS-enabling technology of deploying very large structures have been studied. The second phase included theoretical studies related to

- the assembly of very large structures such as antennas by using novel swarm control algorithms [26]-[28]
- the dynamics and control of the deployment of very large nets [29]-[32]
- robotic options to deploy antenna elements on relatively loose nets [33] [34]

as well as two main experiments:

- *Furoshiki*: a Japanese sounding rocket experiment flown in 2006, demonstrating among others the deployment of antenna elements on very large free floating nets under microgravity [35]-[39]
- *Suaineadh*: a European sounding rocket experiment scheduled to be flown in early 2012, attempting the demonstration of a controlled deployment of a net using centrifugal forces [40][41].

III EUROPEAN ENERGY LANDSCAPE AND PERSPECTIVES

Since the definition of the last reference SPS system and the European SPS Programme Plan in 2002, substantial changes have occurred in the overall energy landscape. This chapter intends to provide a quick overview over the most important ones to be taken into account for a fresh look of space solar power in Europe.

III.1 Continued Increase in Energy Demands

At least up to a certain development level, a direct link exists between the availability of energy and the population size. Between 1950 and 2010, the total world population has been multiplied by a factor 2.7 (2.5 billions in 1950, 6.8 billions in 2010 and expected to reach 7 billions by the end of 2011 [42][43]) while the energy consumption has increased 5.4-fold: the energy consumption in 1950 was about 28000 TWh [44],[45] and rose to 149500 TWh in 2010 [46], equivalent to an annual power consumption rate of 17 TW [47]. Despite a slight decrease in annual energy use in 2009 the first since 30 years (1.5% with respect to 2008), the energy consumption growth rate between 2009 and 2010 was over 5%. Most forecasts for the 21st century predict a further continuous and substantial increase in the world energy demand, expected to more than double by the end of this century.

III.2 Substantial increases in oil and gas prices

When the NASA Fresh Look study was published in 1997, the oil price was below $20 per barrel*, then subsequently dropped to almost $10 before reaching again about $20 per barrel at the time of publication of the ESA SPS Programme Plan in 2002. In the meantime, it experienced a substantial spike of about $140 per barrel just before the economic crisis of 2008/2009. Since the majority of our energy sources come from oil and gas, their price is crucial for any private endeavour towards solar power from space.

III.3 Better understanding of the contributions of the energy system to climate change

With respect to 1997 and to 2002, our understanding of the mechanisms of the climate system have increased spectacularly, not at least thanks to strong international scientific cooperation, data exchange and comparison. Despite remaining uncertainties especially on the error margins of forecasts, the environmental effects of different energy choices and especially its contributions to anthropogenic global warming, start to be well understood, leading to an emerging international consensus on the need to "green" the energy system by reducing it's CO_2 emissions. Large-scale renewable energy infrastructures are seen as part of the solution. Not surprisingly therefore, of all energy sources, solar power has experienced the highest average annual growth rate of 36% between 1999 and 2009 in the world electricity production from renewable energy sources [48].

III.4 Ambitious governmental renewable energy policies

Since 1997 and 2002, many governments and practically all European governments have installed governmental policies and regulatory measures to support the introduction of renewable power sources. The consequences of these policies are clearly visible especially in those European countries with early and ambitious programmes.

While the effects of our energy choices have global consequences and thus a sustainable energy system is also of global interest, different geographic regions

* Brent spot prices

present different natural conditions and characteristics, including the availability of natural resources, consumption patterns, climatic, weather and geographic conditions. In 2008, the EU-27 energy consumption was about 20900 TWh, of which 11800 TWh [49] were net imports (56% on the EU-27 energy consumption), leading to strategic vulnerabilities [50].

In 2007, the European Council adopted ambitious energy and climate change objectives for 2020 [51]: reduction of GHG emissions by 20%, increase of the share of renewable energy to 20% and a 20% improvement in energy efficiency [50].

Due to its geographical situation with high population density and high latitude, many parts of Europe may not be suited for large-scale terrestrial production of solar electricity. However North African Sahara is among the best location worldwide thanks to its high insulation (around 2200kWh/m² on average per year) and low population density.

III.5 Emergence of ambitious private large-scale solar energy projects

Following some interest at the end of the 1970s, there were only very few new large-scale terrestrial solar energy projects except some visionary precursor plants. With low fossil fuel prices at the time of the fresh look study and the definition of the European SPS Programme Plan, arguments in favour of supporting large-scale solar power plants were difficult. Private investors were not able to build up a solid business plan for large-scale terrestrial solar power plants. This situation has changed dramatically. Ambitious solar power plant projects have emerged practically worldwide, the solar photovoltaic industry has emancipated itself from the silicon waver industry, new more efficient and cheaper production processes have been developed as well as substantial efforts have been made in renewable energy research and development.

Energy import dependence discussions and sustained high energy costs have furthermore led to new privately led consortia proposing, large-scale terrestrial renewable energy networks, such as the Desertec project [52].

With all main driving conditions to remain strong, such as energy import dependence, high environmental footprint of the current energy mix, new technologies and large-scale production modes bringing renewable power sources very close to market competitiveness without governmental subsidies, and sustained governmental ambitions to move towards a more sustainable, green energy mix, it is legitimate to suppose that within a timescale of 15-20 years, at least some of these plans will materialise and substantial portions of European electricity demands will be fulfilled by terrestrial solar power plants.

IV CHANGES IN THE SPACE SECTOR WITH RELEVANCE TO SPS

IV.1 Access to space

The end of the Space Shuttle program with the Atlantis STS-135 mission in July 2011 is but one example of the profound changes currently transforming the space sector. More and more countries are entering space activities, and while the sector is still dominated by governmental investments and strategic considerations, private entities are increasingly entering domains, which were previously occupied exclusively by governmental agencies.

Through the COTS (Commercial Orbital Transportation Services) and CCDev (Commercial Crew Development) projects, NASA's Commercial Crew & Cargo Program Office promotes and catalyses private space industry to provide the routine access to space in the post-Shuttle era [53]. In this frame, NASA awarded two contracts in December 2008 to procure a total of 20 cargos to the ISS. At the same time, on December 8th 2010, SpaceX became the first private company to demonstrate the launch and return of a spacecraft from orbit. Between 2011 and 2015, SpaceX and Orbital Sciences Corp. are planning to resupply the International Space Station with their Dragon and Cygnus cargos, respectively. ISS rendezvous and berthing missions of the Dragon cargo is planned for late 2011 (initially scheduled for November 2011, [54] but delayed due to rescheduling caused by the failure of a Russian Progress cargo[55]). SpaceX is announcing launch prices into LEO of $59.5M for 10.45mt with Falcon 9 or $125M for 53mt with Falcon Heavy, i.e. 5700$/kg and 2360$/kg respectively, substantially lower than historic launch costs [56].

In parallel, NASA unveiled on September 14th 2011 its future heavy launcher: known as Space Launch System [57]. It is planned to not only carry the Orion Multi-Purpose Crew Vehicle but also to offer lift capacity of 70mt in its initial version and up to 130mt for a future evolved version.

Both of these trends, the planned lowering of launch costs to 2000-3000 $/kg as well as a new 130 mt launch capacity have the potential to significantly improve the prospects of solar power from space. The last reference study assessment were made with launch costs solidly stable at 10000 $/kg and not prospect of a heavy lift launch capacity available.

IV.2 Small spacecraft

A further trend of potential importance to the overall environment into which solar power from space applications have to be thought is the increasing development of micro and nanosatellites. While having being developed outside the traditional space community, CubeSats constitute already one of the most successful space platforms, providing furthermore a radically different and much easier access to space, enlarging the space community. The CubeSat concept has been introduced in 1999 by the California Polytechnic State University and Stanford University. While first dedicated to education by providing hands-on experience to students, industries started to become interested in this rapidly growing concept. CubeSats and nanosatellites in general indeed offer the possibility to space companies to have easy and cheap flight qualification opportunities [58]. For instance, the NanoSail-D2 3-unit CubeSat developed by the NASA's Marshal Space Flight Center was launched on-board of the FastSat spacecraft in November 2010 and demonstrate the successful deployment of its 3x3m² 7.5µm thick CP-1™ solar sail. Despite their obvious size difference, nanosatellites based SPS technology demonstration missions could be imagined such as intelligent formation flying or thin films photovoltaics sail flight demonstration.

IV.3 Private start-up SPS ventures

More related to space based solar power, some private space companies dedicated to space solar power emerged with business plans credible enough to attract investor funds during the last years [59]-[61]. Those companies aim at promoting and developing space solar power, with a focus on the purely commercial aspects. While the lack of technical information is making judgements on the technical credibility difficult, the general approach from entrepreneurs and not just engineers is certainly an enrichment of the discussions on space solar power and enlarge their spectrum. Along the same line, the announcement of the signature of an actual contract on the provision of solar power from space to one of the big energy utilities helped increasing the visibility of space solar power in the general media [62].

IV.4 Defence interests in SPS

Defence is also getting interested by space solar power. In 2007, the US National Security Space Office Advanced Concepts Office re-assessed the concept feasibility through an open source, internet-based collaboration forum [63]. A second report released in 2009 by US Naval Research Laboratory (NRL) described the possible defence applications and NRL involvement in the development of SPS [64]. In addition to re-affirming the technological feasibility of SPS, both studies highlighted the niche market opportunities than defence could offer to the initial demonstration of SPS.

IV.5 International consensus

In addition to the numerous studies that have been conducted at national levels, only very recently international efforts in forging consensus on the current state of the concept have been successful. In this context, in particular two studies are to be highlighted:

In 2007, URSI (Union Radio Scientifique Internationale) a non-profit, non-governmental association of international scientists released a study reviewing the different SPS concepts and assessing in particular the impact of SPS on radio communication [65]. While the study was initiated and dominated by Japanese researchers, it not only had an international scope but it also involved international contributions in drafting and reviewing the report.

In 2009, work on a study on space solar power under the auspices of the International Academy of Astronautics has been started. Inputs have been collected at international congresses and first versions were reviewed by the IAF space power committee and other interested experts, preliminary findings presented at international congresses for peer review and feedback. The final version has been published in early 2011 [66].

IV.6 Increasing use of prices and challenges

The last ten years has also been characterised by a widening spectrum of how space activities are conducted and space technology is developed, involving at the same time new actors in the space sector. Among the more successful, highly visible and potentially SPS relevant mechanisms are especially prices, challenges and new ways of forming public private partnerships. Space related competitions have proven to be highly successful to attract new actors into the space sector, new sources of funding to develop space related technologies and new innovation processes, such as the Ansari X-Prize, the Google Lunar X-Prize, different DARPA (Defense Advanced Research Projects Agency) challenges or NASA's Centennial Challenges, which organized challenges such as the strong tether, power beaming and space elevator challenges [67]. Especially the power beaming challenge has direct implications to key SPS technologies.

In 2011, a dedicated SPS competition has been initiated by the Online Journal of Space Communication in partnership with the Society of Satellite Professionals International, the National Space Society and the Ohio University GRID Lab.

IV.7 Re-establishment of NIAC

The NASA institute for advanced studies (NIAC) has been re-established in 2010, following a recommendation and a highly positive review by the US National Research Council in 2008 of the performance of the original NIAC, which was operational from 1998 to 2007 [68], [69].

The original NIAC programme was one of the few activity lines within NASA which had a time horizon for its research long enough to include SPS concepts and technologies. The new NIAC has been created with slightly modified operational settings but with similar goals. Among the first round of selected grant proposals, several related to space solar power technologies have been included as well as one dedicated to space solar power itself.

V SPS TECHNOLOGY PERSPECTIVES/ADVANCES

Since the SPS Program Plan in 2002, progress in several technology areas needed for SPS such as solar power generation, large space structures, assembly and automatic docking has been made. A review of some of these technologies is performed hereafter.

V.1 Solar Power Generation

Solar power generation efficiency has always been key to SPS. Among the key figures of merit concerning solar power generation, the specific power [W/kg] is one of the most important and has been the subject of intensive research and improvements [66].

The SunTower SPS concept, assumed 1000W/kg of specific power, while the thin-film based European Sail Tower SPS concept assumed 3500W/kg global specific power (including sail deployment mechanism, 4850W/kg if only taking the sail into account) with 13% efficiency CIS deposited on 7.5µm thick Kapton® foils [7][16].

Since these early 2000s reference concept definitions, many advances have been made concerning solar power generation, supported by the strong terrestrial solar energy development. Two specific areas will be highlighted here: a-Si and CIGS thin films solar cells and new Inverted Metamorphic Multijunctions (IMM) solar cells.

Triple junction a-Si:H/a-SiGe:H/a-SiGe:H solar cells deposited on 25µm thick polymer have already been produced using partial roll-to-roll process [70],[71] and achieving 9.5% AM0 BOL aperture area efficiency leading to a 2343 W/kg BOL specific power (1600W/kg using full roll-to-roll process). In 2007, a demonstrator concept has been introduced [72] based on the development of a-Si:H single junction 0.25cm² cells deposited on 6µm thick LaRC™ CP1 polyimide which have shown a 9.5% AM1.5 efficiency leading to a power density of 3200W/kg, estimated to be 4300W/kg under AM0 [73].

$Cu(In,Ga)Se_2$ (CIGS) thin films solar cell efficiency has always been higher than a-Si based thin films but a-Si had the advantage of being deposited at lower temperature, allowing the use of lighter polymer substrate and therefore higher specific power. Advances in high temperature resistant polymer (such as the a-Si and CIGS thin film substrate dedicated Kapton® PV9100 series [74]) and lower substrate temperature deposition have recently allowed the use of CIGS on flexible polymer. DLR is also investigating CIGS thin film solar cells for space application through the German joint project lead by DLR "flexible CIGSe thin film solar cells for space flight" which has demonstrated 15.5% AM1.5 efficiency (0.5cm² area) and 12.7% AM1.5 on 29.5cm² area based on roll-to-roll production process [75][76]. This field of research is also important in the terrestrial building integrated photovoltaics development and synergies could be envisaged. Current record efficiencies of CIGS on glass substrate are about 20% AM1.5 [77][78] and CIGS on flexible polymer substrate are getting closer to these records: from 14.1% in 2005 [79] to 17.1% in 2010 [80] and 18.7% in 2011 [81] as shown in Fig. 1.

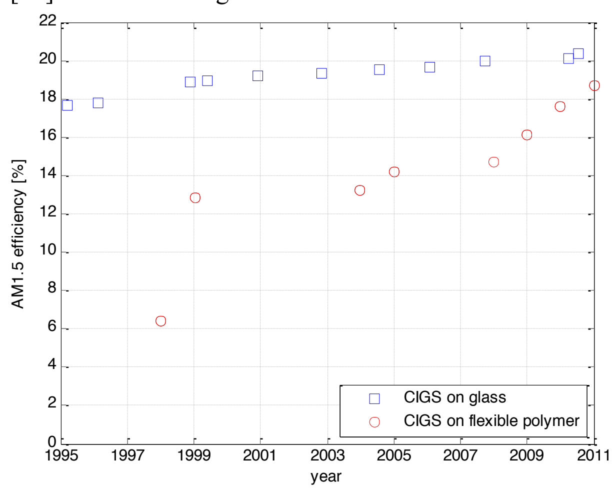

Fig. 1 : CIGS cells efficiency evolution and comparison with flexible polymer deposited CIGS.([78][81][82])

An important aspect regarding durability and EOL performances of SPS is the radiation hardness, especially if the SPS has to go through the radiation belts during orbit raising. From this point of view, a-Si and CIGS thin films solar cells offer another advantage thanks to their inherent radiation hardness [83], [84]. Moreover, a-Si cells exhibit a significant recovery under operational temperatures (60-80°C) thanks to annealing processes.

In parallel to the a-Si and CIGS thin film solar cells development on polymer substrates, new thinned solar cells are being developed: the Inverted Metamorphic Multijunction (IMM, also known as lattice mismatched, first introduced in [85]) solar cells not only allow better efficiency thanks to their upside down growing method but this method also allows to remove the parent substrate. Thin cells (typical thickness of 10µm-20µm [86]) are therefore a direct by-product of the manufacturing process leading to further increase their specific power up to 3650W/kg at the bare cell level [87]. Thinner solar cells also make them flexible, allowing fold-out or roll-out packaging.

In 2008, NREL won the R&D100 Award with the development of such new solar cells, which are now commercialized. On July 20th 2011, EMCORE Inverted Metamorphic Module Quadruple-Junction (IMM4J) solar cells were released from the Space Shuttle Atlantis' cargo bay during its final mission, as part of the MISSE-8 (Materials International Space Station Experiment) FTSCE-III (Forward Technology Solar Cell Experiment) program [88][89]. The solar cells exhibited one of the highest ever measured in-situ efficiency: greater than 33% [90]. Under high concentration, these solar cells could even approach the 50% efficiency, current records being above 42%[77].

In 2010, JAXA reported a 4500W/kg specific power using inverted metamorphic double junction 24.9% AM0 efficient solar cells hoping to reach 6000W/kg with 3J-IMM [91].

AFRL and NRL (US Naval Research Laboratory) have conducted parametric simulations to assess the EOL performances of 3J-IMM based blanket in function of protective material against radiation [92]. They show that specific power >700W/kg (including blanket substrate mass) could be feasible.

Solar concentration is another alternative to increase the specific power of spacecraft solar arrays. One example is the stretched lens array under development for several years. It is a refractive 8x concentrator using deployable linear silicone Fresnel lens and 30% efficient 3J Emcore solar cells. Together with the ATK Space Systems' SquareRigger array platform (SLASR), the BOL specific power is 300-500 W/kg with an areal density of 300-400 W/m^2 [93] and projected to be 240W/kg EOL [94]. A flight demonstration of the SLA (SLA Technology Experiment, SLATE) is planned to fly on-board of the TacSat-IV NRL spacecraft scheduled for launch on September 27th, 2011 into a high elliptical orbit. It will measure the performances of the stretched lens array with Emcore ATJM solar cells in the high radiation environment [95].

V.2 Large structures

One characteristic that is common to all different space segments of SPS concepts is their relatively large size and overall mass. Large lightweight deployable structures are therefore an important area of research, which needs to be advanced to enable SPS. Due to the need of other space applications (space astronomy, large telecom structures, large radar apertures etc), research on large deployable space structures is progressing.

The largest space structure ever built in space is the International Space Station. About 30 launches were required to put the total mass of 417Mt ,with dimensions stretching 100 by 70m into orbit [96]. Fig. 5 shows the eight Solar Array Wings (SAWs), each 35m long and 12m wide and consisting of a deployable mast between two solar cells blankets. Stowed, each SAW is 50cm high, 4.6m long and still 12m wide [97].

A recent study [98] compares different technologies (telescopic booms, coil-able booms, truss structures, inflatable booms, shape memory composites booms and articulated booms) currently available (≥ TRL 6) to develop such structures. It appears that the largest potential length achievable at the moment is about 100m by using coil-able booms. Deployable trusses have been flight proven up to 60m (ADAM - Able Deployable Articulated Mast experiment on the Shuttle Radar Topography Mission in February 2000).

Instead of using a mast or other mechanisms to develop the solar sail, the solar sail demonstrator IKAROS launched by JAXA in May 2010 uses centrifugal forces of a spinning spacecraft to deploy it and to keep it extended. The 14m x 14m solar sail was successfully deployed on June 9th (Fig. 2). It is made of 7.5µm thick polyimide and is partially covered with a-Si thin film solar cells generating 300W at 1AU [99]. The total mass of the sail is 16kg leading to an average areal density of 0.081.6 kg/m².

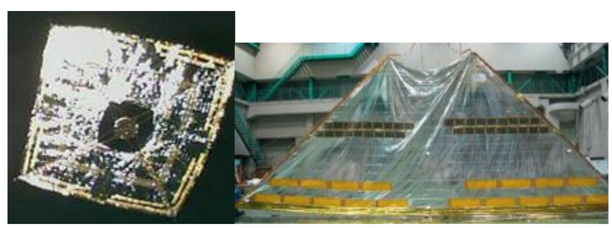

Fig. 2 : Fully deployed solar sail picture taken by the self–operating camera released by IKAROS (left) and one of the four petals of the solar sail with integrated a-Si solar cells in the centre and reflectance control devices for the attitude control near the edges (right). [99]

In mid-2005, the deployment of two 20m x 20m solar sails were demonstrated under vacuum in the NASA 30m Plum Brook Facility [100] (Fig. 3). One used truncated 80m coil-able CFRP masts and 2µm thick aluminized CP1™ thin film while the other used truncated inflatable booms with sub-T_g rigidisation and 2µm thick aluminized Mylar. When extrapolated to 100m, both sails exhibit an areal density below 0.015 kg/m².

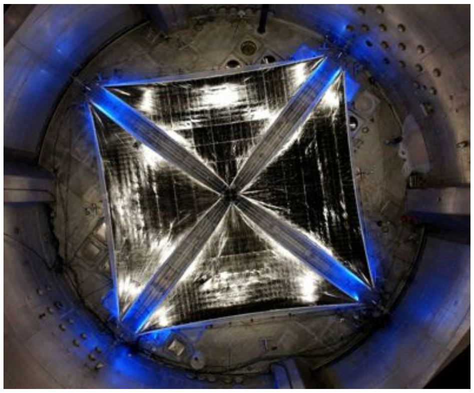

Fig. 3 : Vacuum deployment of a 20m x 20m solar sail made of CP1™ polyimide and CFRP masts in the NASA 30m Plum Brook Facility [100] courtesy of NASA, SRS, ATK-Able

In the frame of the *Furoshiki* experiment, a 130m^2 triangular net has been deployed from a central hub to three daughter spacecraft while performing a short parable during a sounding rocket experiment in 2006 [39].

Due to their ever increasing performances and power requirements, the PV span and antenna size of the telecommunication satellites solar panels has also kept on increasing. The Direct TV12 satellite based on an Boeing 702HP platform is 48m long. The largest antennas used on civilian telecommunication satellites are in the order of 20m (e.g. 19m for the Engineering Test Satellite (ETS)–VIII [101], 22m for the L-band reflector antenna developed onboard of SkyTerra-1 [102] (launched on November 14th, 2010). Some US reconnaissance satellites are reported to have umbrella-like antennas with diameters as large as 100m (e.g. the USA-223 spacecraft launched on November 21st, 2010 onboard a Delta-IV heavy launcher) [103].

Astrophysics missions require ever larger lightweight structures. For instance, the deployable size of the James Webb Space Telescope (JWST) uses multiple deployment mechanisms and complex sequence to deploy its 5 layers 264m^2 (22m x 12m) sunshield.

While there have been steady advances in the deployment of large space systems, there has been no significant breakthrough achieved since the last major space solar power system studies. Further maturation and development is needed in this area.

V.3 High power applications

Along with the size, the electrical power required by satellite has continuously increased, especially for the high power demanding telecommunication satellites. Fig. 4 shows the evolution of the GEO communication satellite power over the last two decades base on the UCS satellites database (May 2011 [104]).

Currently, highest EOL power for telecommunication satellites is about 20kW using the Space Systems/Loral LS1300 platform. European Next generation platforms will provide up to 22kW with the Alphabus extension program [105].

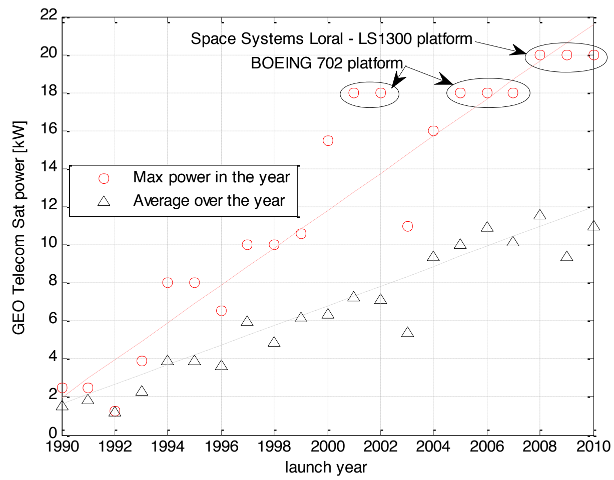

Fig. 4 : Evolution of telecommunication satellites power over the last two decades, based on the satellite database from May 2011 [104].

The International Space Station still holds the record for the highest onboard power. Since March 2009 and the STS 119 mission integrating the fourth and last pair of Solar Array Wings the ISS BOL power generated by the 8 SAWs is about 264kW [97], (208kW 15 years EOL [106]), delivering 84kW usable continuous electrical power, due to Earth and self-shadowing and battery recharging [97][106]. Each solar array wing consists of a 35m long telescopic mast deploying the two array blankets located on both side of the mast and covered with 14.5% BOL efficient solar silicon solar cells [106]. Each wing has a mass of about 1100kg [107] (including the two blankets and the mast), leading to an EOL specific power of 24W/kg. The SAWs operate at a relatively high voltage level of 137V to 173V, which is converted to 124V for onboard power use [106].

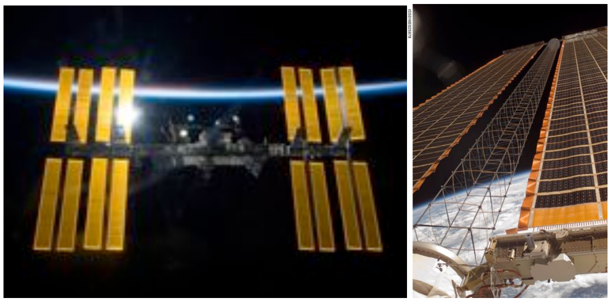

Fig. 5 : ISS Solar Array Wings (SAWs), credit: NASA

V.4 Automated rendezvous & docking

Even today's largest deployable structures are not large enough yet for the needs of space solar power concepts. In-orbit assembly of multiple, separately launched elements is therefore required for the construction of SPS. Ideally, each module should therefore be able to perform an automated rendez-vous & docking with the rest of the structure already assembled. Several substantial advances and demonstrations have been made since 2002 in this domain.

On April 3rd 2008, ESA's first Automated Transfer Vehicles (ATV "Jules Verne") conducted the first fully automated docking with the ISS in full compliance with the very tight safety constraints imposed by human spaceflight operations. The ATV manoeuvring and docking was based on four different instruments: the Russian Kurs radar-based system, the GPS, 2 Videometers and 2 Telegoniometer (laser-pulsed instruments that calculate the distance and orientation to the ISS) [108]. .

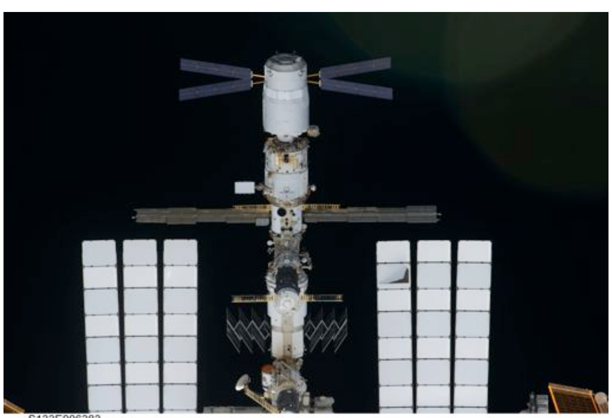

Fig. 6 : ATV-2 Johannes Kepler successfully docked to the ISS and seen from Discovery during the STS-133 mission, credit: ESA

V.5 Robotics and automation

The automated rendezvous and docking is only the first phase of the SPS in-orbit construction: the next crucial phase consists in the assembly of the modules. Since the assembly of large structures by astronauts even in LEO is prohibitively expensive [109], robotic assembly will be necessary for space solar power.

On January 22nd 2006, JAXA conducted a sounding rocket (S-310) experiment aiming at demonstrating several key technologies using the *Furoshiki* concept. One part of the experiment was tested the movements of two autonomous crawling robots provided via ESA's Advanced Concepts Team (called Roby-Space and developed by the Vienna University of Technology - Institute for Handling Devices and Robotics) on the 130m² deployed net in microgravity [35]-[39].

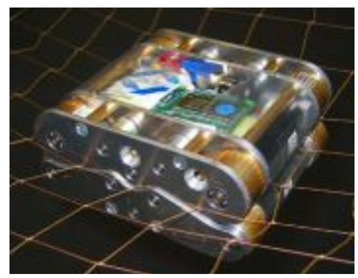

Fig. 7 : Robyspace junior crawling robot prototype [35]

In March 2007, the US Defense Advanced Research Project Agency (DARPA) launched simultaneously two satellites (ASTRO, the chaser and NextSat the target) in the frame of the Orbital Express mission aiming at demonstrating autonomous in-orbit serving capabilities [110],[111]. After being separated from the target by a distance of 7km, ASTRO conducted an autonomous rendez-vous followed by a fly-around inspection. It then captured and berthed NextSat to successfully transfer hydrazine monopropellant, a battery and a flight computer using its robotic arm.

A novel approach to the autonomous assembly of very large structures composed of identical elements has been proposed by the ESA Advanced Concepts Team in 2005 and 2006, using techniques developed for swarm robotics [26][27][112].

Fig. 8 : Orbital Express: ASTRO (left) and NextSat (right) Courtesy of Boeing/DARPA

V.6 Wireless Power Transmission Technologies

V.6.1 Non-mechanical laser beam steering

Transmitting power down to Earth requires high accuracy steering capability. While the technology is well developed for microwave frequencies by using retrodirective antenna systems, non-mechanical beam steering of laser beams is still in its infancy.

Two alternatives exist: mechanical and non-mechanical laser beam steering. Mechanical beam steering using piezoelectric and electromagnetic actuators has already been used for optical laser telecommunications. In 2001, inter-satellite optical data transmission demonstration achieved pointing accuracy of the order of 1µrad [113] between the Artemis spacecraft (ESA) in GEO and SPOT-4 (CNES) in LEO using the SILEX payloads.

JAXA's Optical Inter-orbit Communication Engineering Test Satellite (OICETS) demonstrated the first bi-directional optical communication with Artemis in 2005 and again achieved high accuracy tracking ±1µrad [114]. Mechanical beam steering for wireless power transmission by laser is still considered as suboptimal due to the associated mass and the long-term reliability of moving parts. Non-mechanical beam steering could alleviate some of these concerns. Recent studies conducted since the last SPS reference system studies have demonstrated non-mechanical laser beam steering and tracking using optical phased array based on nonlinear crystals [115] or spatial light modulators based on twisted nematic liquid crystals [116].

V.6.2 Wireless power transmission demonstration

Microwave power transmission is a much better developed area, with a number of key experiments already conducted. One of the early milestones was the experiment at the JPL Goldstone Facility in 1975 transmitting 30kW DC over a 1.6km [117]. Later similar experiments were done for fuel-free airplane tests (SHARP in Canada [118] or MILAX in Japan [119]).

More recently, in 2008, an experiment was conducted to demonstrate the wireless power transmission over a distance as large as 120km between two Hawaii islands using a retro-directive antenna system [120][121].

It is surprising that this technology, which essentially dates back to early experiments by N. Tesla and which has been already applied successfully during the 1960s has not yet found a core application and thus remains still largely confined to underfunded academic research.

VI CONSEQUENCES FOR THE ORIENTATION OF A NEW REFERENCE ASSESSMENT OF SPS

As demonstrated in the previous sections, key technologies enabling solar power from space progressed substantially, though roughly following the expected general advances envisaged 10 years ago. On the other hand, the environment for the introduction of radically new types of energy systems has undergone almost revolutionary changes since the first publication of the European SPS Programme Plan in 2002. The drastic change in the general public perception of the need for real changes has been stronger than anticipated, opening a new window of opportunity for a fresh look at space solar power.

Based on the above-analysed general changes, the following preliminary conclusions are proposed to guide such a fresh look at space solar power, using a special emphasis on the European situation:

- the 20-20-20 energy policy of the European Union is expected to provide the basis and incentives for substantial changes in the European energy infrastructure, including a maintained strong support for the further increase of the share of renewable, and especially solar power sources.
- the rapid development of the terrestrial solar power PV market, accelerated recently by the massive entry of Chinese production will further increase the competitiveness of large-scale terrestrial solar power plants
- the anticipated substantial increase of the share of terrestrial solar power plants is expected to increase the need for the addition of reliable and large-scale energy storage solutions; above a certain total threshold for power from solar energy, energy storage requirements for large-scale solar power plants might drive terrestrial plant costs;

- a real market for large scale terrestrial solar power plants in North-Africa and the Middle East connected to Europe is technically realistic; ongoing and planned private and public investments in such an infrastructure are encouraging and allow the anticipation of 100s of MW to GW scale installations in a 2025+ timeframe
- an orbiting prototype proof of concept of an entire space solar power system is realistic to be assumed in a 2020+ time frame
- contrary to most traditional space applications, the technical aspects of any service from space for the energy sector, including space solar power need to be secondary and driven by economic and service considerations; space for energy needs to be approached radically different than space for science, space for knowledge or space for defence applications; long-term, stable energy sector driven public private partnerships seem to be suitable implementation mechanisms;
- contrary to most solar power from space studies in the past 30 years, the space solar power system needs to be conceived and seen as a complement to and fully integrated into a future terrestrial energy infrastructure, not in opposition to other (terrestrial) options to increase the sustainability of the overall energy system.

VII CONCLUSIONS

Solar power from space has received substantial governmental attention in the late 1970s, partially driven by technical advances, by optimism concerning space projects and by a progressive approach to putting solar power as a cornerstone of the to be changed US energy system by the Carter administration, who announced in 1979, that by the year 2000 20% of the US energy would come from solar energy.[122]

The latest substantial effort to develop a reference design point for space solar power systems was made roughly 15 years later in the late 1990s by NASA. These and some follow-up works were taken as basis for most subsequent reflections on space solar power since then, including some European designs such as the European sail tower.

This paper demonstrates that 15 years later, the space sector has changed substantially, the energy situation is very different from the one of the late 1990s and will likely experience even more profound changes during the next 15 years, key technologies for realising space solar power concepts have substantially advanced and new concerns related to environmental impacts of energy options have all rendered the prospect for space solar more promising than ever before. Based on the combination of the above facts, the paper therefore argues for the need for a third serious fresh look for space solar power and proposed the main framing parameters for such an effort.

REFERENCES

[1] P. E. Glaser, Power from the sun; its future, Science, vol. 162, no. 3856, pp. 857-861, Nov. 22, 1968

[2] R. M. Dickinson and W. C. Brown, Radiated microwave power transmission system efficiency measurements, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, Tech. Memorandum 33-727, May 1975

[3] W. C. Brown, Solar power satellites: microwaves deliver the power, IEEE Spectrum, pp. 36-42, June 1979.

[4] R. M. Dickinson, Beamed microwave power transmitting and receiving subsystems radiation characteristics, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, JPL Publication 80-11, June 1980

[5] The final proceedings of the solar power satellite program review, NASA TM-84183, July 1980

[6] Satellite power system. Concept development and evaluation program, vol. 1 - technical assessment summary report, NASA TM-58232, Nov. 1980

[7] J. C. Mankins, A technical overview of the “Suntower” solar power satellite concept, Acta Astronautica, 50 (6) (2002), 369-377

[8] J. C. Mankins, New directions for space solar power, Acta Astronautica, 65 (1-2) (2009), 145-156.

[9] J. C. Mankins, Space Solar Power: An Assessment of Challenges and Progress, Journal of Aerospace Engineering, 14 (2) (2001), 46-51

[10] N. Kaya, H. Matsumoto, S. Miyatake, I. Kimura, M. Nagamoto, T. Obayashi, Nonlinear interaction of strong microwave beam with the ionosphere – minix rocket experiment, Space Power 6 (1986) 181–186.

[11] H. Matsumoto, Milax airplane experiment and model airplane, in: Proceedings 12th ISAS Space Energy Symposium, ISAS, Tokyo, 1993.

[12] N. Kaya, S. Ida, Y. Fujino, M. Fujita, Transmitting antenna system for airship demonstration (ETHER), Space Energy and Transportation 1 (4) (1996) 237–245.

[13] G. Pignolet, J. Hawkins, N. Kaya, J.-D. Lan Sun Luk, F. Lefevre, V. Loman, Y. Naruo, F. Valette, V. Vanke, Results of the grand basin case study in reunion island:operational design for a 10kw microwave beam energy transporation, in:

Proceedings of the 47th IAC, IAF, Beijing, China, 1996.

[14] Eurospace Future Prospects Group, Powersat - electrical power generation and transmission in space, Final Report 8690/89/F/HEW, European Space Agency, Paris, France (1990).

[15] L. Summerer, F. Ongaro, M. Vasile, and A. Galvez. Prospects for Space Solar Power Work in Europe. Acta Astronautica, 53:571–575, 2003.

[16] M. Klimke, Systemanalytischer Vergleich von erd- und weltraumgestützten Solarkraftwerken zur Deckung des globalen Energiebedarfs, Doctoral Thesis Universität Stuttgart, DLR Forschungsbericht 2001-12, 2001

[17] W. Seboldt, M. Klimke, M. Leipold, and N. Hanowski. European sail tower SPS concept. Acta Astronautica, 48(5-12):785–792, 2001.

[18] M. Zerta, V. Blandow, P. Collins, J. Guillet, T. Nordmann, P. Schmidt, W. Weindorf, and W. Zittel. Earth and space-based power generation systems - a comparison study. In L. Summerer, editor, *Proceedings 4th International Conference on Solar Power from Space SPS'04*, volume SP-567, Granada, Spain, 30 June - 2 July 2004. ESA Publications Division.

[19] V. Quaschning, N. Geuder, P. Viehbahn, F. Steinsiek, and C. Hendriks. Comparison of solar terrestrial and space power generation for Europe. In L. Summerer, editor, *Proceedings 4th International Conference on Solar Power from Space SPS'04,* volume SP-567, Granada, Spain, 30 June - 2 July 2004. ESA Publications Division.

[20] C. Cougnet, E. Sein, A. Celeste, and L. Summerer. Solar power satellites for space exploration. *Journal of the British Interplanetary Society*, 59(8):290–296, 2006.

[21] L. Crapart, P. Achilleas, A. Farand, E. Marescaux, and L. Summerer. Legal aspects of solar power satellites. In *Proceedings International Astronautical Congress IAC'03*, number IAC-03-IISL.1.15, Bremen, Germany, Oct. 2003. IAF - IISL.

[22] H. J. Foth and R. Knappe. Laser power beaming feasibility: non-mechanical beam steering options, laser phase-locking and control. Technical Report 03-2201, European Space Agency, the Advanced Concepts Team, 2004. Available online at www.esa.int/act.

[23] T. Robinson, T. Yeoman, and R. Dhillon. Environmental impact of high power density microwave beams on different atmospheric layers. Technical Report Ariadna 03/9102, ESA Ariadna Final Report, 2004.

[24] M. Leccardi, D. Panzieri, G. Cassisa, and L. Summerer. SPARK – a computerised model for solar power satellite concepts. In L. Summerer, editor, *Proceedings 4th International Conference on Solar Power from Space SPS'04*, volume SP-567. ESA Publications Division, June 30 - July 2 2004.

[25] ESA, L. Summerer, editor. Solar Power from Space - SPS'04, number SP-567, Granada, Spain, June 30 - July 2 2004. ESA Publications Division.

[26] D. Izzo and L. Pettazzi. Self-assembly of large structures in space using intersatellite coulomb forces. In *Proceedings of the 57th International Astronautical Congress*, number IAC-06-C3.4/D3.4.07, Valencia, Spain, October 2006. IAF

[27] L. Pettazzi, D. Izzo, and S. Theil. Swarm navigation and reconfiguration using electrostatic forces. In *Proceedings of the 7th International Conference On Dynamics and Control of Systems and Structures in Space (DCSSS)*, Greenwich, London, UK, July 2006. The Old Royal Naval College.

[28] L. Pettazzi, H. Kruger, and S. Theil. Electrostatic forces for satellite swarm navigation and reconfiguration. Technical Report 05-4107a, European Space Agency, the Advanced Concepts Team, 2006. Available on line at www.esa.int/act.

[29] D. McKenzie, M. Cartmell, G. Radice, and M. Vasile. Space webs. Ariadna Final Report 05-4109b, ESA Advanced Concepts Team, 2006

[30] G. Tibert and M. Gardsback. Space webs. Ariadna Final Report 05-4109a, ESA Advanced Concepts Team, 2005.

[31] M. Gardsback. Deployment Control of Spinning Space Webs and Membranes. PhD thesis, Royal Institute of Technology, Stockholm, November 2008.

[32] M. Cartmell and D. McKenzie. A review of space tether research. *Progress in Aerospace Sciences*, 44(1):1–21, 2008.

[33] P. Kopacek, M.-W. Han, B. Putz, E. Schierer, and M. Wu ̈rzl. A concept of a hightech mobile minirobot for outer space. In L. Summerer, editor, *Proceedings 4th International Conference on Solar Power from Space SPS'04*, volume SP-567, Granada, Spain, June 30 - July 2 2004. ESA, ESA Publications Division.

[34] L. Summerer, B. Putz, P. Kopacek, and N. Kaya. Spider-like robotic mobility for the construction of large antennas in space. In *Proceedings, International Astronautical Congress (IAC'05)*, Fukuoka, Japan, Oct. 2005. IAF.

[35] L. Summerer, B. Putz, P. Kopacek, and N. Kaya. First results of robots crawling on a loose net in micro-gravity during a sounding rocket experiment. In Proceedings, International Astronautical Congress (IAC'06), number IAC-06-C3.3.05, Valencia, Spain, Oct. 2006. IAF.

[36] S. Nakasuka, T. Aoki, I. Ikeda, Y. Tsuda, and Y. Kawakatsu. Furoshiki satellite - a large membrane structure. *Acta Astronautica*, 48(5-12):461–468, 2001.
[37] N. Kaya, S. Nakasuka, L. Summerer, and J. Mankins. International rocket experiment on a huge phased array antenna constructed by Furoshiki satellite with robots. In ISTS'04, Miyazaki, Japan, 2004.
[38] N. Kaya, M. Iwashita, S. Nakasuka, L. Summerer, and J. Mankins. Crawling robots on large web in rocket experiment on Furoshiki deployment. *Journal of the British Interplanetary Society*, 58(11/12):402–406, November/December 2005.
[39] N. Kaya, M. Iwashita, K. Tanaka, S. Nakasuka, and L. Summerer. Rocket experiment on microwave power transmission with Furoshiki deployment. *Acta Astronautica*, 65(1-2):202–205, 2009.
[40] M. Vasile, M. Cartmell, F. Z. Dejene, T. Drysdale, M. A. Flores, M. Y. Gulzar, N. Ismail, M. U. Khalid, M. Li, C. Maddock, P. Mallol, A. Mathieson, M. McRobb, J. O˙berg, O. Purcell, P. Reynolds, W. Ritterbusch, R. Sandqvist, L. Summerer, M. U. Tanveer, G. Tibert, G. Whyte, W. Zafar, and J. Zhang. The suaineadh project: a stepping stone towards the deployment of large flexible structures in space. In *Proceedings 61st International Astronautical Congress*, number IAC-10-C3.4.4, Prague, Czech Republic, October 2010. IAF.
[41] L. Summerer, O. Purcell, M. Vasile, G. Tibert, and N. Kaya. Making the first steps towards solar power from space - microgravity experiments testing the deployment of large antennas. In Proceedings *60th International Astronautical Congress IAC'09*, number IAC-09.C3.4.4, Daejeon, South Korea, October 2009. IAF.
[42] United Nations Population Division, World Population Prospects: The 2010 Revision (United Nations, New York, 2011); http://esa.un.org/unpd/wpp/index.htm
[43] D. E. Bloom, 7 Billion and Counting, Science 29 July 2011, 333 (6042), 562-569.
[44] ExxonMobil, The Outlook for Energy: A view to 2030, 2010
[45] N. Nakićenović, Global Energy Perspectives to 2050 and Beyond, Vienna University of Technology - International Institute for Applied Systems Analysis, International Conference within Austrian EU Presidency, Vienna, 06 March 2006
[46] Enerdata, Global Energy Statistical Yearbook 2011, 2010 Total energy consumption, http://yearbook.enerdata.net/
[47] U.S. Energy Information Administration (EIA), Annual Energy Outlook 2011 with Projections to 2035, DOE/EIA-0383 (2011)
[48] Observatoires des énergies renouvelables Observ'ER, Twelfth Inventory - Edition 2010, Worldwide electricity production from renewable energy sources - Stats and figures series
[49] Eurostat for the European commission, Energy balance sheets 2007-2008, 2010, ISBN 978-92-79-14615-2
[50] European Commission, EU Energy and transport in figures, statistical pocket book 2010, ISBN 978-92-79-13815-7
[51] European Commission, Directorate-General for Energy, Energy 2020 — A strategy for competitive, sustainable and secure energy, ISBN 978-92-79-18869-5, November 2010
[52] Trans-Mediterranean Renewable Energy Cooperation (TREC), Clean Power from Deserts - The DESERTEC Concept for Energy, Water and Climate Security WhiteBook 4th Edition, ISBN 978-3-929118-67-4
[53] NASA Commercial Crew & Cargo Program Office website, accessed on Sept. 15th, 2011, http://www.nasa.gov/offices/c3po/home/
[54] A. Lindenmoyer, COTS status, presentation to the NASA advisory council, Ames Research Center, August 2nd, 2011.
[55] A. Svitak, SpaceX, Roscosmos Cool Their Jets, http://www.aviationweek.com, accessed on Sept. 26, 2011
[56] http://www.spacex.com/, accessed on Sept. 16, 2011
[57] D. Weaver, M. Braukus, J. Harrington, D. Kanigan, NASA Announces Design for New Deep Space Exploration System, Sept. 14th, 2011, http://www.nasa.gov/exploration/systems/sls/sls1.html accessed on Sept. 14th 2011
[58] S. Greenland, C. Clark, CubeSat platforms as an on-orbit technology validation and verification vehicle, Small Satellite Systems and Services - The 4S Symposium 2010, Funchal, Madeira, May 31-June 4, 2010
[59] Solaren website, http://www.solarenspace.com/
[60] Space Energy website, http://spaceenergy.com/
[61] PowerSat Corp. website, http://www.powersat.com/
[62] A. Boyle, PG&E makes deal for space solar power, Apr. 13th 2009, http://www.msnbc.msn.com/, accessed on Sept. 26th, 2011.
[63] National Security Space Office, Space-Based Solar power As an Opportunity for Strategic Security – Phase 0 Architecture feasibility Study, release 0.1, 10 October 2007
[64] W. N. Johnson, Space-based Solar Power: Possible Defense Applications and Opportunities for NRL

Contributions, report of the Naval research Laboratory, NRL/FR/7650--09-10,179, October 2009

[65] H. Matsumoto, K. Hashimoto, Report of the URSI Inter-Commission Working Group on SPS, 2007

[66] J. C. Mankins et al., Position Paper on Green Energy From Space Solar Power – The First international Assessment of Space Solar Power: opportunities, issues and potential pathways forward, International Academy of Astronautics, 2011

[67] NASA Office of the Chief Technologist website, http://www.nasa.gov/offices/oct/early_stage_innovation/centennial_challenges/index.html, accessed on Sept. 26, 2011

[68] NASA Institute for Advanced Concepts, NIAC - 9th annual and final report, Annual Report Performance Period July 12, 2006 - August 31, 2007, Universities Space Research Association and ANSER, Atlanta, GA 30308, US (Aug. 2007).

[69] R. D. Braun, D. S. Wiley, H. W. Brandhorst, D. C. Byers, D. Chinette, I. Chopra, F. D. Drake, O. A. Graeve, M. G. Jones, R. A. Moore, P. E. Muntz, L. R. Young, Fostering visions for the future: a review of the NASA Institute of Advanced Concepts, National Academies Press, Washington DC, US, 2009, http://www.nap.edu/catalog/12702.html.

[70] F. Liu, J. Owens, G. Pietka, K. Beernink, A. Banerjee, J. Yang, and S. Guha, Advances in flexible and ultra lightweight monolithically integrated a-Si:H based triple-junction PV modules made using roll-to-roll deposition, in: 34th IEEE Photovoltaic Specialists Conference (PVSC), Philadelphia, PA, June 7-12, 2009, pp. 1370-1373

[71] S. Bailey, J. McNatt, R. Raffaelle, S. Hubbard, D. Forbes, L. Fritzenmeier, W. Maurer, The Future of space photovoltaics, in: 34th IEEE Photovoltaic Specialists Conference (PVSC), Philadelphia, PA, June 7-12, 2009, pp. 1909-1913

[72] K. Reed, H.J. Willenberg, Early commercial demonstration of space solar power using ultra-lightweight arrays, Acta Astronautica, 65 (2009), 1250-1260

[73] N. Wyrsch, D. Dominé, F. Freitas, L. Feitknecht, J. Bailat, C. Ballif, G. Poe, K. Bates, K. Reed, Ultra-light amorphous silicon cell for space applications, in: 4th World Conference on Photovoltaic Solar energy Conversion, Waikoloa, HI, May 7-12, 2006

[74] Dupont website, Kapton® high performance flexible films for photovolataic substrates, http://www2.dupont.com/Photovoltaics/en_US/products_services/thinfilm_substrates/kapton.html, accessed on Sept. 27, 2011

[75] K. Zajac, S. Brunner, C. A. Kaufmann, R. Caballero, H-W. Schock, A. Rahm, C. Scheit, H. Zachmann, F. Kessler, R. Wuerz, and P. Schülke, Latest results of the German joint project "flexible CIGSe thin film solar cells for space applications", in: 35th IEEE Photovoltaic Specialists Conference (PVSC), Honolulu, HI, June 20-25, 2010, pp. 16-19

[76] K. Zajac, S. Brunner, C. A. Kaufmann, R. Caballero, A. Rahm, C. Scheit, H. Zachmmann, F. Kessler, M. Wagner, New findings of the German joint project "flexible CIGSe thin film solar cells for space flight", in: 34th IEEE Photovoltaic Specialists Conference (PVSC), Philadelphia, PA, June 7-12, 2009, pp. 55-59

[77] M. A. Green, K. Emery, Y. Hishikawa, W. Warta, Solar cell efficiency tables (version 37), Progress in Photovoltaics: research and applications, 19 (2011), 84–92

[78] http://en.wikipedia.org/wiki/Solar_cell, Research Cell Efficiency Plot for Various Photovoltaic Technologies 1976-2011, (26 August 2011)

[79] D. Brémaud, D. Rudmann, G. Bilger, H. Zogg, A.N. Tiwari, Towards the development of flexible CIGS solar cells on polymer films with efficiency exceeding 15%, in: Proceedings of the 31st IEEE Photovoltaic Specialists Conference (PVSC), Orlando, FL, January 3-7, 2005; pp. 223–226.

[80] A. Chirilă, P. Bloesch, S. Seyrling, A. Uhl, S. Buecheler, F. Pianezzi, C. Fella, J. Perrenoud, L. Kranz, R. Verma, D. Guettler, S. Nishiwaki, Y.E. Romanyuk, G. Bilger, D. Brémaud, A.N. Tiwari, Cu(In,Ga)Se2 solar cell grown on flexible polymer substrate with efficiency exceeding 17%, Progress in Photovoltaics: Research and applications, 19 (2011), 560-564

[81] Laboratory for Thin Films and Photovoltaics, EMPA, Swiss Federal Laboratories for Materials Science and Technology, Record efficiency of 18.7% for flexible CIGS solar cells on plastics, May 19, 2011 media release, http://www.empa.ch/plugin/template/empa/*/107442

[82] S. Ishizuka, H. Hommoto, N. Kido, K Hashimoto, A. Yamada, S. Niki, Efficiency Enhancement of Cu(In,Ga)Se2 Solar Cells Fabricated on Flexible Polyimide Substrates using Alkali-Silicate Glass Thin Layers, Applied Physics Express, vol.1, iss. 9, (2008), pp. 092303

[83] J. E. Granata, T. D. Sahlstrom, P. Hausgen, S. R. Messenger, R. J. Walters, J. R. Lorentzen, S. Liu, R. Helizon, Thin-film photovoltaic radiation testing and modeling for a MEO orbit, in: 31st IEEE Photovoltaic Specialists Conference (PVSC), Orlando, FL, January 3-7, 2005, pp. 607-610

[84] S. Liu, J. Granata, J. Nocerino, J. Halpine, E. Simburger, Thin-Film Photovoltaic Radiation Testing for Space Applications, in: 4th World

Conference on Photovoltaic Energy Conversion, Waikoloa, HI, May 7-12, 2006, pp. 1876-1878

[85] M.W. Wanlass, S.P. Ahrenkiel, R.K. Ahrenkiel, D.S. Albin, J.J. Carapella, A. Duda, J.F. Geisz, S. Kurtz, T. Moriarty, R.J. Wehrer, B. Wernsman, Lattice-Mismatched Approaches for High-Performance, III-V Photovoltaic Energy Converters, in: 31st IEEE Photovoltaic Specialists Conference (PVSC), Orlando, FL, January 3-7, 2005, pp. 530-535

[86] M. L. Breen, A. Streett, D. Cokin, R. Stribling, A. Mason, S. Sutton, IBIS (Integrated Blanket/Interconnect System) Boeing's solution for implementing IMM (Inverted Metamorphic) solar cells on a light-weight flexible solar panel, in: 35th IEEE Photovoltaic Specialists Conference (PVSC), Honolulu, HI, June 20-25, 2010, pp. 723-724

[87] A. Cornfeld, J. Diaz, The 3J-IMM solar cell: pathways for insertion into space systems, in: 34th IEEE Photovoltaic Specialists Conference (PVSC), Philadelphia, PA, June 7-12, 2009, pp. 954-959

[88] "Emcore Corporation | Fiber Optics · Solar Power." [Online]. Available: http://www.emcore.com/. [Accessed: 20-Sept-2011]

[89] B. Cho, R. Lutz, J. Pappan, E. Downard, A. Cornfeld, N. Fatemi, M.A. Stan, P. Sharps, C. Su, S. Billets, S. Gasner, A. Howard, IMM experimentation in the next frontier: EMCORE's participation in the MISSE-8 program, in: 35th IEEE Photovoltaic Specialists Conference (PVSC), Honolulu, HI, June 20-25, 2010, pp. 110-112

[90] A. Cornfeld, D. Aiken, B. Cho, A. Ley, P. Sharps, M. Stan, T. Varghese, Development if a four sub-cell inverted metamorphic multijunction (IMM) highly efficient AM0 solar cell, in: 35th IEEE Photovoltaic Specialists Conference (PVSC), Honolulu, HI, June 20-25, 2010, pp. 105-109

[91] M. Imaizumi, M. Takahashi, T. Takamoto, JAXA's strategy for development of high performance space photovoltaics, in: 35th IEEE Photovoltaic Specialists Conference (PVSC), Honolulu, HI, June 20-25, 2010, pp. 128-131

[92] D. Wilt, S. Messenger, A. Howard, Technology opportunities to enable high mass specific power, , in: 34th IEEE Photovoltaic Specialists Conference (PVSC), Philadelphia, PA, June 7-12, 2009, pp. 1500-1506

[93] M. O'Neill, J. Howell, J. Fikes, L. Lollar, C. Carrington, N. Suzuki, M. Piszczor, D. Hoppe, M. Eskenazi, D. Aiken, M. Fulton, H. Brandhorst, M. Schuller, A.J. McDanal, Stretched Lens Array SquareRigger (SLASR): A New Space Array for High-Power Missions, in: 4th World Conference on Photovoltaic Energy Conversion, Waikoloa, HI, May 7-12, 2006, pp. 2009-2009

[94] H. Brandhorst, J. Rodiek, M. O'Neill, Stretched Lens Array: The answer to improving solar array reliability, in: 33rd IEEE Photovoltaic Specialists Conference (PVSC), San Diego, CA, May 11-16, 2008, pp. 1-4

[95] H. Brandhorst, S. Best, J. Rodiek, M. Crumpler, M. O'Neill, H. Lewis, P. McDermott, Accomplishments and objectives of the stretched lens array technology experiment (SLATE), in: 34th IEEE Photovoltaic Specialists Conference (PVSC), Philadelphia, PA, June 7-12, 2009, pp. 1402-1406

[96] NASA website, accessed on 08 Sept 2011, http://www.nasa.gov/mission_pages/station/structure/isstodate.html

[97] STS-119 Press Kit – Full Power, Feb. 2009, http://www.nasa.gov/pdf/304681main_STS-119_Press_Kit.pdf

[98] L. Puig, A. Barton, N. Rando, A review on large deployable structures for astrophysics missions, Acta Astronautica, 67 (1-2) (2010) 12-26

[99] Y. Tsuda, O. Mori, R. Funase, H. Sawada, T. Yamamoto, T. Saiki, T. Endo, J. Kawaguchi, Flight status of IKAROS deep space solar sail demonstrator, Acta Astronatica, 69 (9-10) (2011) 833-840

[100] L. Johnson, R. Young, E. Montgomery, D. Alhorn, Status of solar sail technology within NASA, J. Adv. Space Res. (2011) doi:10.1016/j.asr.2010.12.011

[101] A. Meguroa, K. Shintate, M. Usui, A. Tsujihata, In-orbit deployment characteristics of large deployable antenna reflector onboard Engineering Test Satellite VIII, Acta Astronautica, 65 (9-10) (2009), 1306-1316.

[102] P. de Selding, Boeing Finishes Deployment of Stuck SkyTerra 1 Antenna, December 14th, 2010, http://www.spacenews.com/satellite_telecom/101214-boeing-completes-skyterra-antenna-deployment.html, retrieved on September 13th, 2011

[103] J. Ray, Essential U.S. Spy Satellite Launching Friday, 17 November 2010, http://www.space.com/9551-essential-spy-satellite-launching-friday.html, accessed on September 12th, 2011

[104] Union of Concerned Scientists website, 5-1-11 Satellite Database Downloads, http://www.ucsusa.org/nuclear_weapons_and_global_security/space_weapons/technical_issues/ucs-satellite-database.html, accessed on September 12th , 2011

[105] ALPHABUS: Europe's solution for the high-power satcom market, ESA Bulletin 142, May 2010

[106] International Space Station Electric Power System (EPS), Boeing IDS Business Support, Communications and Community Affairs, 2006,

http://www.boeing.com/defense-space/space/spacestation/systems/docs/ISS%20Electric%20Power%20System.pdf

[107] C. Mansfield, NASA John F. Kennedy Space Center, http://www.nasa.gov/mission_pages/station/behindscenes/truss_segment.html, accessed on September 12th, 2011

[108] EADS Astrium, ATV Jules Verne Launch Kit, March 2008

[109] W. Shen, P. Will, B. Khoshnevis, Self-assembly in space via self-recon figurable robots, in Proceedings of the International Conference on Robotics and Automation, Taiwan, 2003.

[110] K. Yoshida, Achievements in space robotics, Robotics & Automation Magazine, IEEE, vol.16, no. 4, pp. 20-28, December 2009

[111] C. Dennehy, J. Carpenter, A Summary of the Rendezvous, Proximity Operations, Docking, and Undocking (RPODU) Lessons Learned from the Defense Advanced Research Project Agency (DARPA) Orbital Express (OE) Demonstration System Mission, April 4th 2011, NASA report n°: NASA/TM-2011-217088

[112] D. Izzo, L. Pettazzi, M. Ayre, Mission concepts for autonomous on-orbit assembly of a large reflector in space, in: Proceedings, International Astronautical Congress (IAC'05), Vol. IAC-05-D.1.4.03, IAF, 2005.

[113] G. Planche, V. Chorvalli, SILEX in-orbit performances, in: 5th International Conference on Space Optics (ICSO 2004), Toulouse, France, March 30 - April 2, 2004, pp. 403-410

[114] Y. Fujiwara, M. Mokuno, T. Jono, T. Yamawaki, K. Arai, M. Toyoshima, H. Kunimori, Z. Sodnik, A. Bird, B. Demelenne, Optical inter-orbit communications engineering test satellite (OICETS), Acta Astronautica, 61 (1-6) (2007), 163-175.

[115] C. Schäfer, O. Matoba, N. Kaya, Optical retrodirective tracking system approach using an array of phase conjugators for communication and power transmission, Applied Optics, 46 (21) (2007), 4633-4641

[116] C. Schäfer, O. Matoba, N. Kaya, Laser Beam Control Mechanism in 56th International Astronautical Congress (IAC) 2005, number IAC-05-C3.2.10, 2005

[117] E. Hoffert, P. Soukup, M. Hoffert, Power Beaming for Space-Based Electricity on Earth: Near-Term Experiments with Radars, Lasers and Satellites, In Proeedings of the 4th International Conference on Solar Power from Space - SPS '04, together with the 5th International Conference on Wireless Power Transmission - WPT 5, 30 June - 2 July 2004, Granada, Spain

[118] J.J. Schlesak, A. Alden, T. Ohno, A microwave powered high altitude platform, Microwave Symposium Digest, 1988., IEEE MTT-S International, 25-27 May 1988, vol.1, pp 283 - 286

[119] H. Matsumoto, et al., "MILAX Airplane Experiment and Model Airplane," 12th ISAS Space Energy Symposium, Tokyo, Japan, March 1993

[120] N. Kaya, M. Iwashita, F. Little, J. C. Mankins, Microwave Power Beaming Test in Hawaii, In *Proceedings International Astronautical Congress IAC'09*, number IAC-09-C3.4.3, Daejeon, Korean Republic, Oct. 2009, IAF.

[121] N. Kaya, J. C. Mankins, The Second Microwave Power Beaming Experiment in Hawaii, In *Proceedings International Astronautical Congress IAC'10*, number IAC-10-C3.4.5, Prague, Czech Republic, Sept. 2010, IAF.

[122] J. Carter, Televised speech by US President Jimmy Carter delivered on July 15, 1979 (1979).