# ESA work on Solar Power from Space: concluded and ongoing activities

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# Contents

# 1 Introduction

Solar Power Satellites (SPS) that transform sunlight into electric energy and use Wireless Power Transmission, WPT, to transmit this energy, is an interesting concept for sustainable energy production. It can also be an alternative to nuclear power for some space exploration missions. This document is a summary of what has been done in the ESA SPS research activities so far. Due to its potential strategic interest, research on solar power satellites has been an activity of the Advanced Concepts Team in ESA since the very start of the team. The technology is on the one hand not considered mature enough to be taken up within other ESA programmes, on the other hand it is considered too attractive not to be developed further. Therefore, development of supporting technology should be monitored. Recently, new initiatives in space solar power promotion have been taken by US National Security Space Office, through a document on the feasibility of space solar power as a source of clean energy. That document can be downloaded from `http://spacesolarpower.wordpress.com/`. The following text is only intended to give a brief overview of the ESA SPS Programme. However, some texts giving further information as been included as appendices to this document.

# 2 European Network and Programme Plan

Following several system studies done during the 1980's and 1990's within the ESA General Studies Programme, the European Network on Solar Power from Space was created in 2002. The network elaborated a programme plan to support and coordinate ESA's activities in the field. It is included as an appendix to this document. The overall objective is to produce support material for the Agency and its Member States, to evaluate the possibilities of solar power satellites, and to formulate a European strategy for space solar power in the light of sustainable global development. The following specific goals were defined in the SPS Programme Plan:

1. Perform a scientifically sound and objective comparison of space based and comparable ground based power generation solutions.
2. Identification of possible synergies between ground and space based power generation solutions.
3. Assessment of the potential role of SPS for space exploration.
4. Establishment of one to three innovative, realistic and promising SPS concepts.
5. Identification of major technical SPS areas, demanding research and development.

6. Perform two to three feasibility studies for near-term demonstrator missions that provide enough information to support a decision on further activities.

7. Assessment of the most promising ways to integrate SPS into a hydrogen-based economy.

8. Provision of focus, stimulus and coordination to European research on SPS.

9. Identification of promising opportunities for international cooperation.

The ESA SPS programme is divided into three phases;

**Phase 1** assessed the viability of terrestrial solutions comparable to the most recent spaced based solutions, and a first assessment of SPS for space exploration was made. See section 2.1 for more information.

**Phase 2** intends to include feasibility studies of near-term demonstrator missions using SPS and WPT as alternative to nuclear power sources for space exploration and space applications. See section 3 for more info.

**Phase 3** In this phase the Phase 2 feasibility studies are planned to be elaborated up to a level of detail that allows a decision to be taken on whether to initiate the demonstrator missions. The studies will be assembled into a document representing the ESA strategy in the field of SPS which will serve as decision basis for further activities.

## 2.1 Phase 1 outcomes

### 2.1.1 Comparison space and Earth based solar power

In 2003–2005 two independent consortia led by the energy consultants LBST and EcoFys studied Earth based and space-based solar power systems. Their studies were performed in parallel, and the task was to compare the costs, risks and reliabilities of these systems for European power supply in 2025–2030. They set up a number of scenarios making different choices for each scenario regarding the types and sizes of the solar power plants, the type of energy storage used and whether the power was used for base-load or not. These are some of the conclusions that came out of the studies:

- SPS have scaling advantages; they are competitive with terrestrial solutions for larger sizes of power plants.
- The single largest cost factor for SPS systems is the launch.

- Terrestrial and space solar power plants have comparably short energy payback times in the order of months to a few years.
- The studies indicate that for a European scenario, large solar power satellites concepts are competitive to comparable terrestrial solar plants in a 2025–2030 time-frame.

More information about the studies can be found in the short summary document in the appendices.

### 2.1.2 SPS for space exploration

A study made by EADS Astrium SAS, with the University of la Réunion, investigated the possible role of SPS for space exploration and whether solar power satellites could provide a viable alternative to nuclear power sources in the timeframe under consideration for robotic and human Mars exploration (∼2030) as well as for other space applications, such as e.g. orbital platforms. Three specific space mission scenarios were studied:

- large, high power needs for Earth orbiting spacecraft,
- interplanetary missions beyond the Martian orbit,
- Martian and lunar surface missions

The study showed that solar power satellites using wireless power transmission could be an option for powering certain lunar missions but show little potential for powering interplanetary missions or Earth orbiting spacecraft. The executive summary of the report can be found on the ACT publications page: `www.esa.int/act`.

### 2.1.3 SPARK Model

In the SPARK (Solar Power Advanced Research Knowledge) project a technology survey of system level aspects of solar power satellites was performed and a parametric computer model was developed by Alenia Spazio together with Universita del Piemonte Orientale. The need for such a tool derives from the understanding that the range of mission scenarios related to SPS can be very wide covering from tenths of watt for a planet rover battery charging to gigawatts for a station supplying energy to Earth. For each application, the software assesses the expected system characteristics like for example size, mass, launcheability, etc in order to evaluate the feasibility and possible constraints. This allows immediate evaluation of mission feasibility also tracked to the technology trend evolution. The abstract of a paper presented at the SPS conference in 2004 explaining the SPARK project in further detail is included in the appendices.

### 2.1.4 Legal Aspects

The study "Legal Aspects of Solar Power Satellite Concepts" provided ESA with the current legal framework applicable for SPS concepts, listed the applicable branches of law, and highlighted the current limitations and legal requirements for constructing and operating SPS concepts. It was performed by IDEST. A paper written for the IAF Conference 2003, which outlines the subject a little bit more, can be found among the appendices.

### 2.1.5 Conference

Phase 1 of the ESA SPS programme was concluded with the 4th Solar Power from Space conference joint with the 5th Wireless Power Transmission conference. It was organised by ESA in Granada in June 2004. It focussed on the following themes:

- Comparison and Integration of space and terrestrial solar power plant concepts
- Integration of SPS into H2 economy scenarios
- Large-scale terrestrial power supply scenarios
- SPS for space exploration - Science, research and exploration
- Wireless and long-distance power transmission
- Near-term demonstrators and experiments

In addition to the presentations of the results at the conference, the first phase was concluded with a Japanese peer review of the ESA SPS Programme plan.

### 2.1.6 Japanese peer review

The Phase 1 peer review was conducted by Kobe university, involving all major Japanese SPS institutions including JAXA, AIST and USEF. It is a review of the results of the first phase, including the approach. A presentation of the results was held in 2006 and some of the slides from this presentation is included in the appendices of this document.

## 2.2 Phase 1 spin-offs

### 2.2.1 Furoshiki

This sounding rocket experiment tested the most promising concepts to realize light weight, reliable, small, simple and cheap robotic mobility systems for moving and eventually working on a Furoshiki net under microgravity conditions. A detailed concept of the most promising option was elaborated up to fast prototyping maturity level. The project was a cooperation between Vienna University of Technology, Kobe University and University of Tokyo as well as ESA, JAXA and NASA. Following this experiment two Ariadna studies performed by University of Glasgow and the Swedish Royal Institute of Technology investigated "Space Webs" such as the Furoshiki concept. Numerical models for the deployment and stabilisation of the nets were created. The Ariadna final reports and articles on the Furoshiki experiment can be found on the ACT webpage: `www.esa.int/act`.

#### 2.2.2 Space4Energy grid study

The Space4Energy study is an outcome of the SPS conference. The overall objective is to quantify the benefit of space technologies such as Earth observation, telecommunications and navigation satellites for the management of electrical power grids when distributed renewable energy plants are integrated as part of the grid. An improved grid management would result in a better exploitation of the renewable resources as well as in an increased electrical efficiency, grid stability and power quality. More information on this study can be found on the project webpage: `www.space4energy.org/`.

#### 2.2.3 URSI white paper

ESA and ACT actively contributed to the development of the URSI white paper on solar power satellites. It discusses radio-science issues of microwave transmission as proposed in SPS concepts. Such issues include environmental and health issues, interference with communications, remote sensing and radio-astronomy observations as well as technical aspects of microwave power generation and transmission. The paper can be found via the following link: `www.ursi.org/WP/WP-SPS%20final.htm`.

## 3 Current efforts

### 3.1 US Pentagon initiative

In April 2007 the US National Security Space Office started a study "[...] to determine the feasibility of space-based solar power as a source of clean energy that may be able to broadcast power to deployed forces, supplement national power grids, and other smaller applications." The conductors of the study invited interested parties from all over the world to participate in a public discussion preceding the study via discussion groups on the web. The mission was to "[d]etermine the political, scientific, technical, logistical, and commercial feasibility of space-based solar power collection and distribution" and to "[d]iscuss significant capabilities, limitations, and alternatives.

Identify challenges that must be overcome, and suggest a research and development investment plan that incrementally retires risk on the path to fielding an operational system." [1] An interim report was issued on the 10th of October 2007, and got significant attention in the media. The report can be downloaded from this site: `http://spacesolarpower.wordpress.com/`. Currently, the study continues and will focus more intently on certain areas.

### 3.2 Phase 2

Based on the results from the various studies of the first phase of the SPS Programme, the Japanese peer review, and the recent activities in the US SPS community, it is currently proposed to focus the second phase of the programme on the use of the Moon as a test case. A lunar exploration mission would have a reasonable size and would be an interesting candidate for the use of SPS technology as an alternative to nuclear power sources. Such a mission could be used to demonstrate laser power transmission and the integration of space-based solar power into a ground-based system.

## 4 Conclusions

The first phase of the programme plan has been concluded successfully, with several spin-off projects as a bonus. The renewed interest for solar power from space in the US makes this the right time to start off the second phase of the ESA SPS Programme Plan.

[1] Quotations from the public discussion webpage:
http://spacesolarpower.wordpress.com/the-national-security-space-office-study

# 5 List of publications

The following is a list of articles and reports produced within the SPS and Ariadna[2] programmes. Some of them are reports of the studies described in this document, others are conference papers or peer-reviewed articles.

## SPS Study reports


[1] V. Blandow, P. Schmidt, W. Weindorf, M. Zerta, W. Zittel, M. Bernasconi, P. Collins, T. Nordmann, T. Vontobel, and J. Guillet. Earth and space-based power generation systems - a comparison study. LBST Final Report 17682/03/NL/EC, European Space Agency, the Advanced Concepts Team, 2004.

[2] C. Cougnet, E. Sein, D. Loche, A. Celeste, and J. P. Roux. Solar power satellites - SPS REPOSE. EADS Final Report 03/SZ1/317NT/CC, European Space Agency, the Advanced Concepts Team, 2004.

[3] L. Crapart, E. Marescaux, and P. Achilleas. Legal aspects of solar power satellites. IDEST Final Report GSP-02/02/L91, European Space Agency, the Advanced Concepts Team, 2003.

[4] C. Hendriks, N. Geurder, P. Viebahn, F. Steinsiek, and J. Spies. Solar power from space: European strategy in the light of sustainable development. EcoFys Final Report EEP03020, European Space Agency, the Advanced Concepts Team, 2004.

[5] M. Leccardi, M. Taj, D. Panzieri, and G. C. Cassisa. Spark mod. Users Manual SD-MA-AI-0013, European Space Agency, the Advanced Concepts Team, 2003.


## Ariadna Final Reports


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

[7] T. R. Robinson, T. K. Yeoman, and R. S. Dhillon. Environmental impacts of high power density microwave beams on different atmospheric layers. Ariadna Final Report 03-9102, European Space Agency, the Advanced Concepts Team, 2004.


[2]The Ariadna programme is an ACT tool to stimulate research on enabling space research areas and on the development of new design methods. Its main objective is to enhance cooperation and facilitate research partnerships with universities.

## Articles


[8] L. Summerer and F. Ongaro. Où capter l'energie solaire? Comparaison des concepts spatiaux et terrestres. *REE*, (9):82–88, 2004.

[9] L. Summerer, F. Ongaro, M. Vasile, and A. Gálvez. Prospects for space power work in Europe. *Acta Astronautica*, 53:571–575, 2002.


## Conference papers


[10] C. Cougnet, E. Sein, Celeste A., and L. Summerer. Solar power satellites for space exploration and applications. In *SP 567, SPS'04, S5a-54*, July 2004.

[11] C. Cougnet, E. Sein, A. Celeste, and L. Summerer. Solar power satellites for space applications. In *55th International Astronautical Congress, Vancouver, Canada*, October 2004.

[12] N. Kaya, M. Iwashita, S. Nakasuka, L. Summerer, and J. Mankins. Crawling robots on large web in rocket experiment on Furoshiki deployment. In *55th International Astronautical Congress, Vancouver, Canada*, October 2004.

[13] F. Ongaro and L. Summerer. Peter Glaser Lecture: Space and a sustainable 21st century energy system. In *57th International Astronautical Congress, Valencia, Spain*, October 2006.

[14] L. Summerer. Solar power satellites - European approach. In *Japanese Solar Power Conference, Kobe (J)*, - 2003.

[15] L. Summerer. Space and terrestrial solar power sources for large-scale hydrogen production - a comparison. In *Hypothesis V, Sardinia (I)*, pages 233–258, September 2003.

[16] L. Summerer. Space and terrestrial solar power sources for large-scale hydrogen production - a comparison. In *Hypothesis V, Sardinia (I)*, pages 233–258, September 2003.

[17] L. Summerer, M. Ayre, A. Gálvez, F. Ongaro, and M. Vasile. Roles of solar power from space for Europe: Space exploration and combinations with terrestrial solar power plant concepts. In *55th International Astronautical Congress, Vancouver, Canada*, October 2004.

[18] L. Summerer and M. Lang. Solar power from space - an energy source meeting the demand of a hydrogen-based society. In *EHEC03 Grenoble*, September 2003.

[19] L. Summerer and F. Ongaro. Solar power from space-validation of options for Europe. In *SPS'04*, July 2004.

[20] L. Summerer and F. Ongaro. Advanced space technology for 21st century energy systems: Solar power from space. In *RAST05, Istanbul*, pages 16–23, June 2005.

[21] L. Summerer and G. Pignolet. SPS European views: Environment and health. In *URSI, Pisa (I),*, May 2004.

[22] 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 *57th International Astronautical Congress, Valencia, Spain*, October 2006.

[23] L. Summerer, M. Vasile, R. Biesbroek, and F. Ongaro. Space and ground based large scale solar power plants - a European perspective. In *IAC-03/R.1.09*, October 2003.

[24] L. Summerer, M. Vasile, and F. Ongaro. Assessment of an integrated space-terrestrial, solar-based Euro-Asian energy system. In *ISTS 2004-r-39, Miyazaki, Japan*, July 2004.

# APPENDICES

The previous text is only intended to give a brief overview of the various activities performed in the ESA SPS Programme. The following documents have been included as appendices, to give more details:

- **ESA SPS Programme Plan.**
- **Comparing Earth and Space-based Solar Power Generation Systems in Europe** – a brief introduction to the LBST and EcoFys reports.
- **SPARK - A Computerised Model for Solar Power Satellite concepts** – an abstract of an SPS'04 conference paper.
- **Legal Aspects of Solar Power Satellites** – a IAC'03 conference paper.
- **Peer Review on ESA SPS Study** – a shortened version of a presentation held by Professor Nobuyuki Kaya to ESA in 2006.

More information, for example the complete study reports, can be found on the ACT webpage: `www.esa.int/act`.

# SOLAR POWER FROM SPACE – EUROPEAN STRATEGY IN THE LIGHT OF GLOBAL SUSTAINABLE DEVELOPMENT

## Programme plan

| | |
|---|---|
| prepared by/*préparé par* | Leopold Summerer |
| reference/*réference* | ESA SPS Programme plan 2003/2005; GS 03.L36 |
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# TABLE OF CONTENT

# 1 INTRODUCTION

## 1.1 Scope of the Document

This document describes the goal, the strategy and the different phases of the programme "Solar Power From Space - European Strategy in the light of Global Sustainable Development", specifying the high level requirements, the activities and the general deliverables of each of the phases. The programme "Solar Power From Space – European Strategy in the light of Global Sustainable Development" is also called "SPS – Programme" or only the "Programme".

This Programme plan (PP) describes the overall working plan on the Programme in the timeframe 2003-2005 and serves as guideline for all activities and studies to be conducted in the frame of the Programme. Is is considered as a "living" document that follows the progress of the work and adapts to its development. It will be attached as an annexe to all individual Statements of Work for studies performed under the Programme.

## 1.2 Background

This chapter presents first a short overview over the global energy situation today, including an outlook over the timeframe of this Programme. The general motivation for the two main applications of SPS to be discussed in this Programme, power generation for Europe and for space exploration are outlined in paragraphs 1.2.2 and 1.2.3.

### *1.2.1 Global Energy Situation*

Until the 18th century, the energy need for human activities was taken from renewable biomass burning. The industrial revolution, starting in the mid 19th century was based on coal burning, peaking in the early 20th century, when almost 80% of humanities energy need was taken from coal. During the same period, the total need for energy steadily increased, more or less in parallel with world population. The energy needs for the even faster evolution of the 20th century was based on oil and gas burning, successively lowering the shares of coal, which continued to increase in absolute terms. Since the oil crisis in the 70s, while still increasing in absolute terms,, the share of oil and gas levelled at about 60% for the benefit of nuclear energy, representing now about 15% of the of the total global energy supply.[1] While human population has quadrupled in the 20th century, primary power consumption has increased 16-fold.[2]

All forecasts for the 21st century agree on a continuous and substantial increase in the worldwide energy demand. History tells us, that the availability of affordable energy and the level of development are closely liked. The current increase in energy consumptions is

[1] International Energy Agency, World Energy Outlook 2002; *OECD/IEA*, 2002
[2] J.R. McNeill, *Something New Under the Sun: An Environmental History of the Twentieth Century*, Norton, New York, 2000

already mainly driven by developments in developing countries. This trend will be reinforced within the next 50 years. By the end of this century, the total primary energy requirements will double in the most optimistic case, assuming radical changes, massive, global scale investments into renewable energy sources and/or high global inequity, and increase 5-fold under normal realistic growth assumptions, supposing "only" improvements in energy density. The 2002 worldwide energy requirement is about 1.061e14 kWh.[3]

In the last years, the fossil fuel greenhouse theory has become more and more credible as we continue – based on an increasing number of scientific observations – to better understand the links between fossil fuel burning, climate change and environmental impacts. All factors indicate that the additional power requirements of the 21st century, in any case several times the entire present level, should come from $CO_2$ emission free energy sources. In a recent review article in *Science* 18 US scientists compared the different technical solutions to the energy problem of the 21st century. Solar power satellites as well as terrestrial renewable options were identified as one promising option for the 21st century.[4]

Based on the technical state of the art of the year 1995, NASA proposed a $CO_2$ emission free space based solution after a 2 year trade-off study.[5] During the last 10 years, some concepts for large scale terrestrial renewable energy plants have been forwarded. A preliminary assessment of the possibility to fulfil the global energy need with a worldwide network of solar thermal collector plants and high voltage transmission lines was presented in 1999.[6]

## 1.2.2 Solar Energy for Europe – European Specificities

While the energy generation for the development of the 21st century is a global problem, each region presents its own characteristics, determined by the availability of natural resources, climatic and geographic conditions. Today, Europe is depending to 50% on energy import. The dependence is expected to grow up to 70% until 2020, implying strategic vulnerability especially since there is only a limited number of supply regions[7]. Europe has furthermore taken the lead in international programmes to reduce the global $CO_2$ emission level and bears at least some moral burden to show the example. While the target is a 7% reduction of its emissions until 2008/12 compared to 1990, the actual trend shows a 5% increase, calling for substantial changes.
This Programme shall limit its considerations in the field of renewable, $CO_2$-emission free terrestrial energies to solar power plants. Other sources might be taken into consideration as a supplement, e.g. to reduce storage needs.

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[3] Energy units should be given in [kWh]. Power units should be given in [W]. Numbers in [Btu], [toe], [J], [erg] and [calories] shall all be converted into [kWh].
[4] Hoffert et al.; Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet; *Science, Vol 298*, p. 981ff, November 2002
[5] NASA; Space Solar Power – A fresh look at the feasibility of generating solar power in space for the use on Earth, *NASA Report* Nr. SAIC-97/1005, 1997
[6] M. Klimke; *Systemanalytischer Vergleich von erd- und weltraumgestützten Solarkraftwerken zur Deckung des globalen Energiebedarfs*, Doctoral Thesis Universität Stuttgart, DLR Forschungsbericht 2001-12, 2001
[7] Green Paper "Energy – Towards a European strategy for the security of energy supply"; *European Commission*, ISBN 92-894-0319-5; 2001

For a strategic comparison between terrestrial and space based renewable, $CO_2$ emission free energy systems, geographic characteristics play an important role in addition to other parameters like development, availability of resources and infrastructure. In this respect, the conclusions for Japan for example are most likely completely different than the ones for Europe, or Africa. For the use of direct solar irradiation for large scale energy generation, Europe itself has in fact two major disadvantages in this respect: a relatively high population density and thus limited amount of unused, cheap land surfaces, and its geographical location quite far from the equator. On the other hand, the worldwide best suited region for generating power via direct solar irradiation, the North African Sahara is very close. Since the timescales of SPS Programme is in the order of 20 to 30 years, it is legitimate to suppose a closer economic and political involvement of the North African region into Europe, including the use of Sahara for power generation.

### *1.2.3 Energy for Space Exploration and Space Applications*

Power is one of the enabling crucial elements of space missions. Since the very beginning the importance of efficiently using the only abundant power source in space: solar power was recognized and most of the spacecraft are solar powered. Until now, physics limits the efficient use of solar power to a sphere around the sun extending approximately until the Martian orbit since the available power level per $m^2$ decreases with the power of 2 as the distance increases. This physical limitations lead to the use of nuclear power sources for planetary missions further than Mars. Nuclear power sources (NPS) are also considered as one of the options for energy intensive robotic and human Mars missions.

Recent progress in space solar power satellites and wireless power transmission (WPT) suggest that applications of space solar power systems may provide an alternative to nuclear power sources in certain cases. This seems to be valid as well for an eventual Earth Mars transportation system as well as to power planetary surface stations. Within the considered timeframe, the possibility to supply Earth bound orbital platforms could also be an option.

One of the current arguments in favour of NPS for Mars missions is that solar powered Mars exploration is only possible in the near equator regions, while water is expected rather at polar regions. SPS and WPT would overcome this limitation of on surface photovoltaic devices. Europe does not possess NPS, extensively used as RTGs by the US and in form of fission reactors by the Soviet Union and Russia. The development of NPS capabilities in Europe would require significant resources.

This study will thus also investigate roughly three different options for supplying solar power from space to space: The power supply of exploration missions beyond low Earth orbits and whether solar power satellites could provide a viable alternative in the timeframe under consideration for robotic and human Mars exploration (~2030), the supply of power to large power-demanding spacecraft in Earth orbits and the supply of power to Earth orbiting space stations.

## 1.3 Overall Goals of the Programme

Based on the above considerations, the entire Programme works towards the following goals, that are be specified in detail in the description of the work plan of the Programme under section 2:

- Perform a scientifically sound and objective comparison of space based and comparable ground based power generation solutions,
- Identification of possible synergies between ground and space based power generation solutions,
- Assessment of the potential role of SPS for space exploration,
- Establishment of one to three innovative, realistic and promising SPS concepts,
- Identification of major technical SPS areas, demanding research and development,
- Perform two to three feasibility studies for near-term demonstrator missions that provide enough information to support a decision on further activities
- Assessment of the most promising ways to integrate SPS into a hydrogen-based economy,
- Provision of focus, stimulus and coordination to European research on SPS,
- Identification of promising opportunities for international cooperation.

The overall Programme shall be divided into three logical phases.

## 1.4 Objectives of the Work

The overall objective of the work is to produce support material for the Agency and its Member States to evaluate the possibilities of Solar Power Satellites and formulate a European strategy for space solar power in the light of sustainable global development.

## 1.5 Definition of Terms

The following terms should be used during the entire Programme in all documentation and correspondence, at the Programme as well as at the study and contractor and subcontractor level in order to achieve consistency of terms.

| | |
|---|---|
| Programme | also called “SPS Programme” or “entire Programme” makes reference to the overall entire effort as described in this document, lasting about 18 to 24 month and being subdivided into several individual studies. |
| Study | shall be the name used for the individual studies performed within the SPS Programme. |
| System architecture | shall mean a complete end-to-end solution for delivering space solar power to a designated user; it comprises several system concepts and includes all space and ground elements |
| System | shall mean a key system-level design approach; it is typically defined in |

| | |
|---|---|
| concept | terms of technology used |

For the purpose of this document, 'shall', 'should' and 'desirable' or 'optional' are used to define the priority of the requirements, activities or deliverables, with the meaning described by:

- 'shall' are mandatory;
- 'should' are strongly recommended, but may be replaced by a different technical solution with equivalent or better functionality or deleted for well justified reasons;
- 'desirable' or 'optional' are not mandatory but improve the quality and value of the Technical proposal if converted into 'shall'.

'Should' and 'desirable' / 'optional' requirements or activities remaining in the Technical proposal shall be, in agreement with the ESA Technical Representative, converted to 'shall' requirements or activities, or deleted during the negotiation phase or after the necessary investigations have been performed.

## 1.6 ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| ACT | Advanced Concepts Team |
| CDF | Concurrent Design Facility |
| ESOC | European Space Operations Centre |
| ESTEC | European Space Research and Technology Centre |
| ISS | International Space Station |
| NPS | Nuclear Power Sources |
| PP | Programme plan |
| PRR | Preliminary Requirements Preview |
| SMP | Study Management Plan |
| SoW | Statement of Work |
| SPS | Solar Power Satellites |
| TBC | to be confirmed (by the Agency) |
| TBD | to be determined (by the contractor) |
| TBS | to be specified (by the Agency) |
| TT | Topical Team |
| WPs | Work Packages |
| WPT | Wireless Power Transmission |

## 1.7 REFERENCE DOCUMENTS

The following documents and studies shall constitute the basis of the work and be known by all participants:


- ESA/DLR; System Concepts, Architectures and Technologies for Space Exploration and Utilisation (SE&U Study), *European Space Agency Contract Report*; 1999
- Space Solar Power – A Fresh Look At the Feasibility of Generating Solar Power in Space for Use on Earth; Science Applications International Cooperation, Futron Corporation, NASA; NASA Report Number SAIC-97/1005, 1997
- P.Glaser, F. Davidson, K. Csigi; Solar Power Satellites; edt: John Mason, *John Wiley & Sons*, 1998


The following, non-exhaustive list of documents on the subject provide valuable information and should be known by all participants:


- International Energy Agency, World Energy Outlook 2002; *OECD/IEA*, 2002
- W. Seboldt, M. Klimke; European Sail Tower SPS Concept, *Acta Astronautica* Vol. 48, No.5-12, pp. 785-792, 2001
- M. Klimke; *Systemanalytischer Vergleich von erd- und weltraumgestützten Solarkraftwerken zur Deckung des globalen Energiebedarfs*, Doctoral Thesis Universität Stuttgart, DLR Forschungsbericht 2001-12, 2001
- National Research Council; *Laying the Foundation for Space Solar Power – An Assessment of NASA's Space Solar Power Investment Strategy*, National Academy Press, Washington, 2001
- Green Paper "Energy – Towards a European strategy for the security of energy supply"; *European Commission*, ISBN 92-894-0319-5; 2001
- G. Pignolet, The case study for microwave power transportation in Réunion island; Space Energy and Transportation, Vol. 4, No 3,4; 1999
- G. Pignolet et al.; Demonstrating SPS Technologies on Earth: SPS-IdR Studies in Réunion Island towards point-to-point operational WPT ; *Space Energy and Transportation*, Vol. 1, No3, 168ff, 1996
- National Research Council; *Electric Power From Orbit: A Critique of a Satellite Power System*, National Academy Press, Washington, 1981
- Office of Technology Assessment; *Solar Power Satellites*, NTIS No. PB82-108846, Washington, US Government Printing Office, 1981
- P. Glaser; Power from the Sun: Its Future, *Science*, Vol. 162, No 3856, pp 857-866, 1968

# 2 DETAILED PHASE DESCRIPTION

## 2.1 PHASE 1: GENERAL VIABILITY PHASE

### 2.1.1 General Description

The worldwide primary power requirement in 2002 is about 12 TW. By mid of this century, humanity most probably will need several times this amount. The fossil fuel greenhouse theory has become more and more credible as we continue – based on an increasing number of scientific observations – to better understand the links between fossil fuel burning, climate change and environmental impacts. All factors indicate that the additional power requirements of the 21st century, several times the entire present level, should come from $CO_2$ emission free energy sources. Based on the technical state of the art of the year 1995, NASA proposed a $CO_2$ emission free space based solution after a 2-year trade-off study.[8] During the last 10 years, some concepts based on large-scale terrestrial renewable energy sources have been forwarded. A preliminary assessment of the possibility to fulfil the entire worldwide energy need with a worldwide network of solar thermal collector plants and high voltage transmission lines was presented in 1999.[9] In a recent review article published by 18 outstanding US scientists in *Science*, solar power satellites as well as terrestrial renewable options were identified as one of the promising solutions for the 21st century.[10]

**Power from space for terrestrial use**

In the case of power for terrestrial uses, this phase shall assess the viability of terrestrial solutions comparable to the most recent space based solutions as proposed by NASA, the ESA/DLR SE&U study and in Japan (ISAS, NASDA). No new space based systems shall be developed during phase I, but the fully calculated ones shall serve as reference. Special attention shall be given to specificities of the European situation. The power levels proposed in the NASA Fresh Look Study and the ESA/DLR SE&U study range from several hundreds of MW to several hundred of GW, depending on the targeted consumer market. In the SE&U study, the supply of about 500 GW, the European need in 2020 was discussed.

In particular, this phase will address the following questions:
1. Provision of base load power:
    - Geostationary solutions as designed by the Reference Study and the Fresh Look Study would provide 24 hours baseload power. In order to deliver baseload power with terrestrial renewable energy plants, located at the same geographical longitude as the consumer, combinations of solar power plants with either other

[8] NASA; Space Solar Power – A fresh look at the feasibility of generating solar power in space for the use on Earth, *NASA Report* Nr. SAIC-97/1005, 1997
[9] M. Klimke; *Systemanalytischer Vergleich von erd- und weltraumgestützten Solarkraftwerken zur Deckung des globalen Energiebedarfs*, Doctoral Thesis Universität Stuttgart, DLR Forschungsbericht 2001-12, 2001
[10] Hoffert et al.; Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet; *Science, Vol 298*, p. 981ff, November 2002

renewable power sources available during evening hours and at night (e.g. wind power), or storage capacities seem to be necessary. What would be the most favourable solution with nowadays technology as well as with realistic technology advances in 20 to 30 years, in terms of production and material costs, reliability and risk? How these solutions would compare to the internationally proposed space based solutions for the different power levels studied?

2. Provision of peak load power:

   In a first step towards a substantial increase of the power share from renewable energy sources, the provision of only peak load power could be an option. Space based options would then probably be global and in LEO or MEO.

   - How these space-based options would compare to terrestrial options in terms of production and material costs, reliability and risk? The comparison shall be on power levels assessed for the peak load power models of the space based solutions.

3. Combination of terrestrial and space based systems:

   Until now, no thorough assessment has been published, focussing on potential synergies between terrestrial and space based architecture concepts.

   - Could an appropriately chosen space based system supplement terrestrial options?
   - How would a space based system compare with terrestrial $CO_2$-free solutions (e.g. wind, storage)?

     Consumer electricity load peaks in Europe are occurring in the morning and evening hours, with some variations between the different months of a year. Solar power electricity generation capacity usually peaks in the early afternoon hours (all local time).
   - Can the choice of an appropriate orbit significantly reduce the required storage capacities of terrestrial power plants?

4. Viability of the concepts in terms of energy return times

   All in all, the energy balance of a terrestrial and space based system has to be largely positive, assuring a clear net energy return over a reasonably lifetime. Preliminary ESA internal assessments taking into account only orders of magnitude show a positive net energy balance over the projected lifetimes of currently proposed systems.

   - A more in depth assessment shall provide reliable values including realistic maintenance and operations energy costs, material processing and production energy costs as well as servicing energy demands for some of the NASA Fresh Look Study and the ESA SE&U study designs. These values shall be compared to values for terrestrial power plants.

It is important in this phase, that – for the first time – research groups focussed on terrestrial renewable energy plant solutions work closely together with researcher working on space based solutions, linking the research communities and providing the assessment additional credibility.

5. Legal aspects of solar power satellites

   - Solar power satellites constitute in any proposed design a project of worldwide attention and global dimension. The novelty of such an endeavour implies a lack of understanding of the legal implications, calling for an early stage assessment of the legal aspects under some of the important branches of law most probably concerned: international law including space law, environmental law, treaties on disarmament and frequency allocations in the frame of ITU. The possibilities and possible restrictions caused by the existing legal framework shall be assessed during the first phase of the Programme.

**Power from space for space exploration**

Power availability is one of the crucial enabling elements of space exploration. Until now, nuclear power sources are required for longer planetary surface missions as well as missions further than Mars. As outlined in section 1.2.3, recent progress in space solar power satellites and wireless power transmission however suggest that applications of space solar power systems may provide an alternative to nuclear power sources in certain cases.

6. Solar Power Satellites as viable power sources for space exploration and applications
    - Based on existing data, is shall be assessed whether solar power satellites could provide a viable alternative in the timeframe under consideration for robotic and human exploration, with special emphasis on Mars (~2030).
    - In space solar power generation capabilities at power levels suitable for in space applications shall be assessed.
    - A technical feasibility and resulting system architecture level trade-off for three specific space mission scenarios shall be done:
        - large, high power needs for earth orbiting spacecraft,
        - interplanetary missions beyond the Martian orbit,
        - Martian and lunar surface missions

The Agency is considering organising workshops and seminars to accompany the work undertaken in this phase. Each of the workshops would aim to elaborate on specific aspects of the different options for energy-generation, -transportation and storage. Experts in the respective fields will provide insight into the state of research and foreseeable developments. The workshops are intended to be open to interested participants, especially from the European Network on SPS.

The entire Programme has also to be seen in the frame of the ongoing efforts in the field of energy research in the frame of the 6$^{th}$ European Framework Programme (6$^{th}$ FP) on Research. In this respect, the participation in the Expression of Interest (EoI) ESSPERANS (Annex B) to create a European Network of Excellence has to be taken into account throughout the entire Programme. More specifically, the work addressing tasks 1 to 6 shall include paragraphs especially targeting the aims of ESSPERANS.

### *2.1.2 Study Structure*

Tasks 1 to 4 as listed above will be addressed within a single study. In order to ensure the objectivity and widely accepted credibility of the comparisons and tradeoffs included, the study will probably be managed neither by advocates for terrestrial solar power solutions nor space solar power solutions but by an "independent" entity, that should ideally lead a consortium regrouping space and terrestrial competence, thus including research groups

having demonstrated research, development and implementation experience with terrestrial solar plants and research groups with demonstrated experience in the study of space solar power satellite solutions.
A mid-term review is foreseen to show approximately three month after kick-off the first results of a preliminary comparison of space and terrestrial power generation solutions.

For the assessment of the legal aspects of solar power satellites (task 5), academic expertise in pure space law as well as telecommunications law deems required. The study of legal aspects of solar power satellites will be performed by a research centre focussed on these branched of international law. This study would last approximately 3 to 4 month and is quite small scale.

The study addressing task 6 of the first phase will be done separately. Is will be approximately the same length than the study dealing with tasks 1-4. This study requires thorough knowledge of space power needs, especially for exploration mission and competence in laser generation as well as laser power transmission.

Based on the results of the studies addressing tasks 1 to 6, a more general assessment will be made by the ESA Technical Officer assisted by the Topical Team. This assessment will take into account among others the following important parameters:

- technical risks,
- strategic and political risk,
- innovation generation capabilities,
- potential ecologic impacts,
- spin-off capabilities,
- potential health effects.

Several studies should be undertaken in close cooperation with the Advanced Concepts Team (ACT) at ESA. The ACT is supposed the be integrated in the work and data exchange should be kept between the ACT and the contractors.

## 2.2 PHASE 2: SYSTEM ARCHITECTURE LEVEL TRADE-OFF

### 2.2.1 *General Description*

In phase II, a limited system architecture level trade off study shall be performed. The study shall build upon the outcome of the NASA Fresh Look Study and the ESA SE&U study. It shall take into account the legal framework, determined during phase I. The main focus of the trade-off study shall be on

- new and innovative concepts, offering substantial improvements to existing models,
- the identification of technology areas,
    - o that demand further research and development for SPS to be realized,
    - o in which European industry and research institutes already have demonstrated international leadership,

  - that show near- to mid-term potential in other areas than SPS;
- the establishment of roadmaps specific to the identified priority research areas,
- the possible integration of SPS concepts into future energy systems (e.g. hydrogen based energy systems),
- *the assessment of the potential role of SPS concepts for space exploration,*
- the identification of one to three most promising concepts.

The exact content of the work to be performed under phase II depends heavily on the findings during phase I. ESA internal assessments however come to the conclusion, that space based and Earth based systems with comparable power delivery capabilities range in the same order of magnitude in terms of overall cost. The further description of phase II is based on these findings, which still have to be either confirmed or confuted during the detailed assessment of phase I.

Despite the inherent global nature of most of the SPS concepts for power for Earth use, the trade-off study shall focus on the specific European situation. In case of potential promising synergies between ground and space based power plants as outcome of the phase I of the Programme, these aspects shall receive special attention. The overall energy pay-back times shall be assessed for all forwarded concepts and compared to other $CO_2$ emission free solutions.

In case of potential promising possibilities of solar power satellites to substitute nuclear power sources for exploration missions, a system-architecture level trade off shall identify two to three concepts fulfilling the requirements.

Phase II will start at earliest after the mid-term review of the study on terrestrial alternatives scheduled during phase I of the Programme and it shall last about 6 months.

### *2.2.2 Study Structure*

Without anticipating the outcome of Phase I, the work performed under Phase II will most probably have to be performed in a single study, lasting about 6 month.

## 2.3 PHASE 3: TECHNOLOGY FOCUS AND DEMONSTRATOR MISSION SELECTION

### *2.3.1 General Description*

Phase III of the Programme will focus on the few technology areas, identified during phase II. Promising, feasible near term, Earth or space based demonstrator missions will be identified and two to three feasibility studies for such missions will be elaborated in coherence with the roadmap elaborated during Phase II.

These feasibility studies will also include the assessment of possibilities of international participation. Priority will be given to overall cost and expected technological benefit. Taking into account the European participation in the ISS programme, the possibilities the ISS is offering and the international nature of both the ISS and future SPS activities, special attention will be given to potential demonstrator missions making use of the ISS.

The feasibility studies are planned to be done up to a level of details that will allow at the end of Phase III, based on the elaborated documents, to initiate if appropriate such a demonstrator mission. For this purpose, these feasibility studies will provide in addition to the technical details enough managerial and economic information to allow for such a decision to be made under regular conditions. The feasibility studies should be furthermore performed in a way that is suitable to smoothly follow-on with a phase-A study at the ESA CDF facility.

Phase III should last about 7 to 8 month.

At the end of phase III, the different studies will be assembled into a consolidated document representing the European strategy in the field of solar power satellites, including the feasibility studies, which will serve as decision basis for further activities.

### *2.3.2 Study Structure*

The Structure under Phase III is most likely to be performed in a single study, addressing all the aspects listed above.

# 3 PROGRAMME ORGANISATION

The entire Programme is subdivided into several individual studies that will be in themselves consistent and individually handled. They will furthermore integrate into the entire plan as outlined in this document and be part of the final Programme report at the end of the Programme period.

## 3.1 PROGRAMME SCHEDULE

The Programme is divided into three phases:

- PHASE I: GENERAL VIABILITY PHASE

Duration: 5 to 6 months
Studies: Assessment of comparable terrestrial solutions (for Europe) with possible synergies from space systems
Legal aspects of SPS
Assessment of space solar power options for space-to-space power transmission applications

- PHASE II: SYSTEM ARCHITECTURE LEVEL TRADE-OFF

Duration: 6 months
Studies: System Architecture Trade-off Study
Integration of space systems with terrestrial solar plants (optional)

- PHASE III: TECHNOLOGY FOCUS AND DEMONSTRATOR MISSION SELECTION

Duration: 7-8 months
Studies: 2-3 feasibility studies for near-term demonstrator missions for selected identified technology priorities for Europe

## 3.2 STUDY STRUCTURES

Each individual study shall have the following study milestones:

| # | Milestones |
|---|---|
| SM1 | Kick-off |
| SM2 | Mid-term Review |
| SM3 | Study Final Presentation |

## 3.3 Programme Management

### 3.3.1 Programme Plan (PP)

This Programme Plan (PP) is intended to define and organise all the activities within the Programme.
The PP will provide the overall guideline for the entire programme and serve as reference frame for the individual studies. The PP is prepared by the ESA Technical Officer and made available to all members of the European Network for Solar Power Satellites as well as any other interested party or contractor. It is kept updated by the ESA Technical Officer as necessary throughout the programme. Major changes will be discussed with the Topical Team.

### 3.3.2 Topical Team (TT)

In order to assist the ESA Technical Officer in the management, organisation and project controlling of the Programme, a Topical Team has been established. It comprises individuals with demonstrated expertise and experience in the field of Solar Power Satellites.

### 3.3.3 Studies

Each study will have an individual Statement of Work, a Study Organisation Plan and clearly defined milestones and deliverables. The organisation of the activities to be performed within this contract will be detailed by the Contractor into Work Packages. Studies have to fulfil the overall Programme requirements as outlined in this document. A close cooperation between the contractors and the ESA Advanced Concepts Team is planned.

### 3.3.4 Deliverables

At the end of each phase, it is planned to issue intermediate reports by the ACT, assembling the different studies performed during the phase.
The detailed list of deliverables of each individual study will be laid out in the studies SoW. The final reports of the studies will be available in MS Word format, following some basic formatting rules determined by ESA in order to facilitate their integration.

#### 3.3.4.1 Technical Documents

The language to be used for all study deliverables will be English. All documents should be delivered in MS Word format.

## 3.4 PROGRAMME DURATION

The tasks identified in this programme should be accomplished in not more than 2 years.

# ANNEXE A.1

# OVERVIEW OF MAJOR STUDIES ON SOLAR POWER SATELLITE

The general idea to make use of solar irradiation in space as energy source was present already in the very first publications about space exploration by the Russian visionary and father of modern space travel Konstantin Tsiolkovski. The idea was proposed in a concrete way in 1968 by the Czech-US engineer Peter Glaser. Some smaller studies and experiments validating parts of the concepts were undertaken, leading to the exhaustive NASA/DoE "Reference Study" of 1977-1981.

One of the major experiments was the wireless transmission of about 30 kW over a distance of 1.54km at 2.388 GHz made by JPL at the Goldstone facility in the Mojave Desert. The measured μ-wave transmission efficiency was as high as 82%, leading to an overall system efficiency of about 52%. Motivated by the oil crisis, the reference study addressed several different aspects of SPS and came up with the "reference design": a constellation of 60 geostationary satellites each beaming 5 GW via μ-wave to designated ground stations around the globe. Most importantly, it concluded that there where no principal technical "show-stoppers" to the concept.

In 1981 two studies, "Electric Power From Orbit: A Critique of a Satellite Power System"[11] and "Solar Power Satellites"[12], restated the principal feasibility but came also to the conclusion that the urgent energy need from SPS does not exist, that there were several major technical challenges still to overcome and that the economic basis was too thin for the time being. Following this assessment, the DoE/NASA working group was dissolved.

Activities continued on a system level basis and smaller scale. Some important experiments were undertaken especially in the field of wireless power transmission via μ-wave (Canada, Japan). In the early 1990s, interest in SPS rose on an international level. Following the first SPS symposium 1986 in Paris, the SPS91 in Paris, the SPS92 in Rio in the frame of the UN Environment and Development summit, as well as the inclusion of the power sessions in the annual IAF congresses demonstrate the international dimensions. Following the 1979 study

[11] National Academy of Sciences, Electric power from orbit: a critique of a satellite power system; National Academy Press, 1981

[12] Office of Technology Assessment, Solar Power Satellites; Report OTA-E-144, 1981

by the Japanese electronics research society, and recognizing the strategic importance for the archipelago, the Japanese industry and trade ministry MITI integrates the ISAS working group on SPS at the end of 1980s.

Between 1995 and 1997, NASA conducted a new "complete" SPS study, the "Fresh Look Study", followed in 1998 by the Space Solar Power Concept Definition Study and in 1999 by the "Space Solar Power Exploratory Research and Technology Programme (SERT). In parallel, Canada initiated the "Canadian Space Power Initiative", Japan studied the Fresh Look options for Japan in 97 and 98 before initiating a dedicated own SPS programme managed by NASDA in 1999 and to be finished with the end of the Japanese fiscal year in 2003. In Europe CNES restudied the concept issuing in 1999 the report "*Nouvelles perspectives des centrales solaires spatiales et de la TESF*". Solar power from space was also studied within the ESA "Space Exploration and Utilisation (SE&U)" study by DLR, developing the European Sail Tower SPS concept.

**Table 1: Important SPS dates, studies and conferences (preliminary).**

| | | |
|---|---|---|
| 1925 | idea the Konstantin Tsiolkovski | Russia |
| 1968 | SPS proposal by Peter Glaser | USA |
| 1968-72 | NASA (+DoE, ETA, NRC, NAS) SPS evaluation | USA |
| 1975 | JPL WPT Goldstone experiment, Mojave desert | USA |
| 1978-80 | "Concept Development and Evaluation Programme" (CDEP) by the Energy Research and Development Administration (ERDA) | USA |
| 1979 | DoE/NASA Reference Study | USA |
| 1979 | ESA Study "European Aspects of Solar Power Satellites"[13] | ESA |
| 1986 | SPS86 Symposium in Paris/Gif sur Yvette | F/international |
| 1987 | Project "Stationary High Altitude Relay Platform (SHARP)" for WPT by Canadian Ministry for Communication | Canada |
| end 80s | Lunar soil utilisation studies include SPS | USA |
| 1990 | inclusion of Space Power sessions into IAF conferences | international |
| 1991 | SPS91 Symposium in Paris | F/international |
| 1992 | SPS92 Symposium in Rio de Janeiro | Brasil/international |
| 1992 | ISU SSP'92 Design Project on Solar Power Satellites | Japan/International |
| 1993 | Project ISY-METS, WPT and space plasma interactions | Japan |
| 1993 | WPT93 Conference, San Antonio | USA |
| 1993 | UNESCO World Solar Summit, Paris | F/international |
| 1994 | KEPCO and Kobe Univ. Study on terrestrial WPT appl. | Japan |
| 1995 | WPT95 Conference, Kobe | Japan/international |
| 1995-97 | NASA "Fresh Look Study" | USA |
| 1997 | SPS97/WPT97 Symposium, Montréal | Canada |
| 1997-98 | The Canadian Space Power Initiative | Canada |
| 1998 | NASA "Space Solar Power Concept Definition Study" | USA |
| 1998 | WPT demonstration at La Réunion | France |
| 1999 | ESA Study "Space Exploration and Utilisation" | ESA |
| 1999-01 | NASA "Space Solar Power Exploration Research and Technology Programme" (SERT) | |
| 2001 | WPT01 Conference, La Réunion | France |
| 2001 | Laying the Foundations for Space Solar Power: An Assessment of NASA's Space Solar Power Investment Strategy, National Research Council | NASA |

[13] Ruth, J., Westphal, W., Study on European Aspects of Solar Power Satellites; ESA-CR 3705/78/F/DK(SC), 1979

# ANNEXE A.2

# ESSPERANS – EXPRESSION OF INTEREST FOR A NETWORK OF EXCELLENCE IN THE $6^{TH}$ FP

# *Expression of Interest for*
# *An Integrated Project for*
# *Advancing Knowledge on Enabling Technologies for Sustainable Energy Systems*:

"Energy, Space, Solar Power, Environment: Research Actions for a New Society" :

## ESSPERANS

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## Rationale

This integrated project aims to address the research priority 1.1.6.1.ii *"Research activities having an impact in the medium and longer term for sustainable development, global change and ecosystems"*. It focuses on new and advanced concepts in renewable energy technologies with a very significant future energy potential for the world and EU energy supply and requiring long term research to make these technologies competitive with conventional fuels.

Its departure point is the following: clean and abundant energy supply for the future is one of the most critical problems facing humanity in the coming decades: first, fossil fuels are "finite" in the mathematical sense, and, new, abundant, clean and renewable future energy sources should be introduced without delay ; second, by ejecting into the Earth atmosphere in about one century a significant fraction of the carbon accumulated during billion years, the equilibrium of the ecosystem is strongly perturbed, and a global and durable solution should be anticipated now in order to stop this trend.

As such, these problems can only be handled by holistic and world scale approaches that require long term research, development and demonstration, as well as mobilising considerable resources, both in expertise and funding. On the other hand, every means to immediately reduce the $CO_2$ emissions and the energetic dependency on fossil fuels should be introduced. This is particularly crucial for the EU energy supply independence.

Therefore, the integrated project ESSPERANS is conceived as a cluster of research actions which should be developed following a roadmap leading to the introduction at the Earth scale of clean, abundant, and renewable energy sources.

## Objectives

They are listed below in a kind of chronological order, from medium term to long term objectives; this means that the integrated project ESSPERANS should organise research activities in a progressive way following a technology roadmap to be established in order to develop the enabling technologies at the right time and if possible before (or in collaboration with) USA and Japan. The predicted time frame goes from today to 2040. The cluster of planned research actions aims to:

A ] Develop means to immediately reduce the use of fossil fuels
B ] Develop the use of Decentralised Energy Resources
C ] Develop direct hydrogen combustion technologies
D ] Develop $CO_2$ capture and recycling technologies for very large power systems

E ] Develop clean and cost effective production methods of hydrogen
F ] Develop clean and cost effective production methods of electricity

**[ Objectives A, B, C ]** **To contribute to achieve these objectives, which are relatively medium term objectives, ESSPERANS will develop research actions on high efficiency Gas Turbines, focusing on**

- Gas turbine fuel flexibility, hydrogen / natural gas mixtures-hytane, catalytic combustion, high efficiency hydrogen driven gas turbines
- Liquid biofuels, gasification of biomass to produce $H_2$-rich clean syngas
- Hydrogen combustion technology for gas turbines

These research actions could be developed by consortia such as AFTUR (Alternative Fuels for Industrial Gas Turbines, a $5^{th}$ FP project starting in Fall 2002) composed of 21 partners from 8 member states, and supported by EuMIGT. The AFTUR consortium could be enlarged to other partners, from industry (including energy utilities) and academia.

Research actions on hydrogen combustion technologies will rely on the expertise of European combustion science and technology community, organised in EU member states as sections of the International Combustion Institute (head quarters in Pittsburgh, PA, USA) and also co-ordinated by the Federation of the European Sections of the Combustion Institute, which also include the sections of Russia, Poland, Hungary and Turkey.

It is important to mention here the potential synergy between priority 1.1.6 on Sustainable development, global change and ecosystems, which is addressed in this integrated project and the priority 1.1.4. on Aeronautics and Space, through the development of safe $H_2$ combustion technologies for the implementation of ultra-clean aircraft using liquid hydrogen as fuel (project Cryoplane).

Another research action should focus on

- Fuel Cell /Gas Turbine hybrid systems for decentralised energy production.

To conduct this kind of research activity, the integrated project ESPERANS should co-operate with Integrated Projects on Fuel Cells especially those active on high temperature fuel cells (SOFC).

**[ Objective D ]** **To achieve this objective, the integrated project ESSPERANS aims to develop research actions on**

- $CO_2$ recycling to produce CO and Oxygen or to produce $CH_4$

In order to avoid the difficult problem of $CO_2$ storage after its capture from large scale fossil fuel plants, research actions on recycling $CO_2$ should be developed in collaboration with integrated projects on $CO_2$ capture. Several options should be investigated and demonstrated, such as :

- Catalytic transformation of $CO_2$ into CO and Oxygen.

The technology for such transformations exists; they should be evaluated in co-operation with appropriate NoEs and Integrated Projects. Again, the potential synergy with priority 1.1.4 on Aeronautics and Space should be mentioned as the capture and transformation of Martian CO2 into oxygen and CO are today important R&D topics both for ESA and NASA, for Mars mission using in situ resources.

- The captured CO2 could be transformed into CH4 by processing it with H2.

This process obviously needs cost effective hydrogen production (see below).

**[ Objective E ] Clean and cost effective production of $H_2$.**

Hydrogen is expected to become a major energy vector, opening important industrial markets on hydrogen production, storage, transportation, its direct combustion or use in fuel cells. Cost effective and clean production technologies will play a crucial role in this process. Electrolysis (or dissociation) of seawater with photovoltaic electricity appears to be the best option. This needs low cost solar cells such as hybrid solar cells and the use of Earth or Space Solar Energy for electricity production (see below). This research action should be conducted together with NoEs and Integrated Projects active in PV technologies.

**[ Objective F ] Clean and cost effective production of Electricity**

For the clean and abundant production of electricity in the long term, the only sustainable approach is the transformation of solar energy into electricity. There are two sub options: Earth based or Space based, including their combination. Space Solar Energy necessitates low cost space access technology and therefore should be conducted together with Integrated Projects in space propulsion and transportation.

One of these options is to install very large PV farms on orbit or, for example, on the Moon, to convert the electricity into microwaves or laser beams and to beam it down to Earth, to orbital platforms or to spacecraft, for example, to provide power to satellites, or to spacecraft using electric propulsion for orbit change or planetary missions. Giga-watt scale space solar electricity production units are envisaged and their global feasibility has been assessed in the US by NASA and DoE and in Japan by METI. The European Space Agency has also recently acknowledged this development. Europe should not be absent in the development of this long term technological challenge, which may well be the ultimate solution for sustainable energy supply to the Earth for the next century.

As above, this objective can induce a strong synergy with the priority 1.1.4 on Aeronautics and Space, especially to promote a large market for low cost and/or reusable launcher technologies, therefore to support the European space transportation industry and to support the European satellite industry by providing abundant power in orbit. Furthermore, research on the Space Solar Energy objective is expected to induce several innovation spin offs, e.g. in wireless power transmission and laser technologies, where European SMEs can be major players. In this area strong co-operation with Russian institutes should be sought of.

## Need and Relevance

Priority 1.1.6 clearly indicates that new and advanced concepts in renewable energy technologies are needed and that focus should be put on technologies with a significant future energy potential and requiring long-term research integrated at the European level.

The Integrated Project ESSPERANS aims to start innovative research to advance knowledge for enabling technologies to set the path for future clean and abundant electricity and hydrogen production. As explained above, ESSPERANS is conceived as a cluster of projects to be implemented progressively, in order, first, to reduce the use of fossil fuels for energy production and, later, to introduce the intensive use of solar energy for poly-generation of electricity and hydrogen.

This ambitious objective necessitates the integration of several expertise domains, activities, and resources. The time scale of such a project is several decades. Therefore, the European mobilisation is mandatory to continuously pursue the efforts and also to make the necessary links with similarly ambitious projects in preparation in the USA and Japan.

## Scale of ambition and critical mass

As stated above, the ambition of ESSPERANS is to contribute to solve the energy problem of Europe, to sustainable world scale development and to the control of global change. It consists of several steps that should contribute cumulatively to this objective.

The progressive introduction of hydrogen (or more and more hydrogenated fuels) as fuel into gas turbines is one such objective. This will increase the potential of distributed production of clean energy, together with innovative technologies such as CO2 capture and recycling and fuel cells. The mastering of the combustion technologies for advanced industrial gas turbines will also open the way to the use of hydrogen in car engines and aeronautics.

Clean and abundant production of hydrogen from seawater is another objective. Poly-generation of hydrogen and electricity from solar energy is the ultimate objective. Intermediary objectives are the development of low cost and/or reusable space launchers, the mastering of the development of large orbital structures by robotics, the development of wireless power transmission and high power laser technologies.

Europe has the capability to assemble the critical mass to advance simultaneously on these cumulative objectives and ultimately attain the global objective of clean and abundant energy production for sustainable development. Since mid-nineties, USA (NASA and DOE) and Japan (METI) are considerably increasing their efforts towards the same direction, in particular in hydrogen combustion technologies and space solar energy. The European Union should not be absent in this long term challenge and should be able to demonstrate its ability to develop and implement such large scale and ambitious projects.

To achieve this objective, a strong and long term effort should be devoted to support Industries and Research Centers, on extended multidisciplinary system studies together with basic and applied R&D programs, especially in the fields of hydrogen combustion technologies, low cost space propulsion and transportation systems, high efficiency solar energy conversion and transmission systems. The Consortium ESSPERANS is aiming at contributing to this objective.

## Integration

The integration aimed at by ESSPERANS is multi-faceted. Multidisciplinary integration is mandatory regarding the diversity of expertise needed to achieve the cumulative objectives. Integration of various activities is needed to progressively develop the necessary knowledge basis to implement the aimed technologies and to demonstrate them. Advanced hydrogen fuelled gas turbines are one example of activity integration; development and demonstration of solar space power technologies are another example. ESSPERANS will also very strongly contribute to the strengthening of the European Research Area by promoting connections and co-operation between various research and technology communities active in areas such as combustion and propulsion, gas turbines, hydrogen production, storage and transport, fuel cells, space transportation, solar cells, wireless power transmission, lasers, etc. In order to sustain such a multi-faceted project in the long term, it is also mandatory to train students in innovative, multidisciplinary and multi-cultural curricula (including social, financial, risk and international law aspects of large scale projects), to the establishment of which ESSPERANS will contribute.

The names and the expertise areas of the partners supporting this EoI, at this stage, are listed below.

| PARTNER | COUNTRY | TYPE | AREAS of EXPERTISE | CONTACT |
|---|---|---|---|---|
| CNRS-EPEE-LCSR | FR | REC | Energy, Combustion, propulsion | I. Gökalp |
| CNRS-Aérothermique | FR | REC | Space Propulsion | J-C. Lengrand |
| CNRS-CORIA | FR | REC | Energy, Combustion, propulsion | M. Ledoux |
| EADS-LV | FR | IND | Space transportation | H. Hollanders |
| CEA-RIPAULT | FR | INS | Fuel cells, solar cells, Energy | A. Varoquaux |
| IFP | FR | INS | Gas Turbines, Energy | E. Lebas |
| AUXITROL | FR | IND | Sensors, Aeronautics | O. Legras |
| Prospective2100, EDF | FR | ORG | Energy | L. Deschamps |
| Univ. Cath. Louvain | BE | UNIV | Combustion, Emissions | J. Vandooren |
| Univ. Beira Interior | PT | UNIV | Combustion, Propulsion | J. Barata |
| Tech. Univ.Lisbon | PT | UNIV | Energy, Combustion, Hydrogen | M. Carvalho, M. Heitor |
| CRES | GR | INS | Biomass, Energy | C. Panoutsou |
| Agri. Univ. Athens | GR | UNIV | Biomass, Energy | G. Papadakis |
| Cardiff Univ. | UK | UNIV | Combustion, Energy, Biomass | N. Syred, T. Griffiths |
| Queen Mary &WC | UK | UNIV | Combustion, Gas Turbines | C. Lawn |
| UMIST | UK | UNIV | Combustion, Energy | Y. Zhang |
| Cranfield Univ. | UK | UNIV | Combustion, Energy | J.B. Moss |
| ENEA | IT | INS | Energy, Combustion, Gas Turbines | G. Giuseppe |
| Univ. Naples | IT | UNIV | Energy, Combustion | A. Cavaliere |
| CNR-IRC | IT | REC | Energy, Combustion | F. Beretta |
| Univ. Roma Tre | IT | UNIV | Energy, Biomass | G. Cerri |
| Univ. Firenze | IT | UNIV | Energy, Gas Turbines | F. Martelli |
| Nuove Pignone | IT | IND | Gas Turbines | H. Bornemann |
| ESA | NL | ORG | European Space Agency | M. Lang |
| Univ. Twente | NL | UNIV | Energy, Combustion, Biomass | J.B. Kok, E.A. Bramer |
| KEMA | NL | ORG | Energy, DER, Combustion, CO2 | P. Welberg |
| KTH | SE | UNIV | Energy, Combustion, Gas Turbines | T. Fransson |
| TPS Termiska Processer | SE | IND | Energy, Biomass, Hydrogen | L. Waldheim |
| Univ. Lund | SE | UNIV | Energy, Combustion, Gas Turbines | M. Alden, T. Torisson |
| Univ. Zaragoza | ES | UNIV | Energy, Combustion | J. Ballester |
| CIEMAT | ES | UNIV | Energy, Solar | P.L. Garcia-Ybarra |
| Hungarian Acad. Sci. | Hongrie | REC | Energy, Combustion | S. Dobe |
| RIAME | RU | INST | Space Propulsion | V. Kim |

# Comparing Earth and Space-based Solar Power Generation Systems in Europe

During 2004 and 2005, two different consortia, lead by the independent energy consultants, LBST and EcoFys, made two parallel studies with ESA Advanced Concepts Team. The goal was the same for both studies; to compare terrestrial and space based solar power systems for European power supply in 2025-2030 regarding **costs**, **risks** and **reliability**.

This is a short introduction to the project and its results. To read the executive summaries or the full reports of the evaluations go to:
http://www.esa.int/gsp/ACT/publications/index.htm

In short the companies carried out the studies by defining specific system architectures and calculating the levelized costs (LEC) and energy payback times (EPT) for different scenarios using these architectures.

## System architectures

The LBST consortium chose the following system architectures:

- **Terrestrial alternative one:** Photovoltaics (PV) integrated in roofs and facades.
- **Terrestrial alternative two:** Central receiver solar power plants (SOT) with a gross output of 220 $MW_{e}$.
- **Space-based alternative one:** 'Sun Towers' (ST) from the NASA Fresh Look Study, in medium altitude earth orbit, transmitting microwave radiation to rectennae on ground.
- **Space-based alternative two:** Several modular 'Solar Disk' (SD) systems from the NASA Fresh Look study, in geo-stationary orbit transmitting microwave radiation.

Launch costs were treated as an open parameter; therefore the pure comparison between terrestrial and space systems without launch costs led to upper limits for the space systems costs. Above these limits they would not be competitive with terrestrial systems, even with zero launch costs.

| | **Base-load** | | | | **Non-base load** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Terrestrial** | | **Space** | | **Terrestrial** | | **Space** | |
| | **H2** | **Pumped hydro** | **H2** | **Pumped hydro** | **H2** | **Pumped hydro** | **H2** | **Pumped hydro** |
| **0.5 GW** | SOT | SOT | ST | ST | PV | PV | ST | ST |
| **5 GW** | SOT | SOT | SD | SD | PV | PV | SD | SD |
| **10 GW** | SOT | SOT | SD | SD | PV | PV | SD | SD |
| **50 GW** | SOT | SOT | SD | SD | PV | PV | SD | SD |
| **100GW** | SOT | SOT | SD | SD | PV | PV | SD | SD |
| **150 GW** | | | | | PV | PV | SD | SD |
| **500 GW** | SOT | SOT | SD | SD | | | | |

**Table 1:** LBST scenarios matrix; each SOT (Solar power plant), ST (Sun Tower), SD (Solar Disk) or PV (Photovoltaic) represents one scenario

The EcoFys consortium chose these system architectures.

- **Terrestrial alternative one:** Photovoltaics.
- **Terrestrial alternative two:** Solar thermal power plant (SoTh) with a Eurothrough-2 collector and molten salt storage.
- **Space-based:** SPS in geo-stationary orbit with concentrators the same size as the solar cells. Energy transmitted via laser to PV receivers on ground, which also receive terrestrial irradiation.

They also made a discussion of how costs and efficiencies of these technologies might change in the future, and calculated separate scenarios based on that.

| | **Base-load** | | | **Non-base load** | | |
|---|---|---|---|---|---|---|
| | **Terrestrial** | | **Space** | **Terrestrial** | | **Space** |
| | **Molten salt** | **Pumped hydro** | **Pumped hydro** | **Molten salt** | **Pumped hydro** | **Pumped hydro** |
| **0.5 GW** | SoTh | PV | | | | |
| **5 GW** | SoTh | PV | | SoTh | PV | |
| **10 GW** | SoTh | PV | SPS | SoTh | PV | SPS |
| **25 GW** | | | SPS | | | SPS |
| **50 GW** | | | SPS | | | SPS |
| **100GW** | SoTh | PV | SPS | SoTh | PV | SPS |
| **150 GW** | SoTh | PV | SPS | SoTh | PV | SPS |

**Table 2**: EcoFys scenarios matrix; each SoTh (Solar Thermal), PV (Photovoltaics) or SPS (Solar power satellites) represents one scenario.

## Scenarios

The scenarios in Table 1 and Table 2 combine different choices such as:

- Base-load or non-base load power generation.
- Energy storage with hydrogen or pumped hydro.
- Different power levels.
- Different combinations of space-based and terrestrial power generation.
- Geographical sites for terrestrial solar power and rectennaes, in North Africa or in the European sunbelt.

Both consortia also evaluated scenarios combining space-based and terrestrial power generation. These are not shown in the matrices above.

For all the scenarios the Levelized Energy Costs (LEC) and the Energy Payback Times (EPT) were calculated.

## Results

As can be seen in Table 3, Table 4 and Table 5, the two consortia answer the question "Can SPS compete with terrestrial solar power?" differently, due to the initial assumptions and scenarios they set up.

Following the absence of fundamental technical showstoppers as resulted from the NASA Fresh Look Study, some conclusions from the studies are:

- SPS have scaling advantages; they are competitive with terrestrial solutions for larger sizes of power plants. This can best be seen in Table 3**.**
- Placing large-size terrestrial solar power in North Africa rather than in southern Europe makes the terrestrial solutions more competitive than the space-based one. This explains part of the advantages of terrestrial scenarios in the EcoFys report, see Table 5**.**
- SPS is more competitive than terrestrial solutions using hydrogen storage, but less competitive than solutions using pumped hydro.
- The single largest cost factor for SPS systems is the launch.
- Terrestrial and space solar power plants have comparably short energy payback times in the order of months to a few years, with SPS payback times being slightly shorter.
- **These studies indicate that for a European scenario, large solar power satellites concepts are competitive to comparable terrestrial solar plants in a 2025-2030 time frame.**

| | BASE LOAD scenarios | NON-BASE LOAD scenarios |
|---|---|---|
| Terrestrial scenario with pumped hydro *) | SPS not competitive to terrestrial scenarios | ≥ 100 GW with final launch costs: 323-366 EUR/$kg_{payload}$ **) |
| Terrestrial scenario with hydrogen storage | ≥ 50 GW with final launch costs: 411-480 EUR/$kg_{payload}$ **) | ≥ 100 GW with final launch costs: 625-1,060 EUR/$kg_{payload}$ **) |

*) pumped hydro is only limited available in Europe
**) final launch costs are based on cost reduction assumptions for expendable launchers

**Table 3:** LBST Space scenarios which are economically competitive with terrestrial scenarios

| | | 0.5 GW | 5 GW | 10 GW | 50 GW | 100 GW | 500 GW |
|---|---|---|---|---|---|---|---|
| TERRESTRIAL | SOT with reference system acording to DIN [years] | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| | SOT without reference system [years] | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.6 |
| SPACE | SPS with reference system acording to DIN [years] | 2.0 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| | SPS without reference system [years] | 4.4 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |

**Table 4:** LBST Energy payback times for terrestrial and space based solar power

| | Terrestrial base load | | | | SPS base load | |
|---|---|---|---|---|---|---|
| | PV | | Solar Thermal | | | |
| | LEC *(Euro/kWh)* | EPT *(years)* | LEC *(Euro/kWh)* | EPT *(years)* | LEC *(Euro/kWh)* | EPT *(years)* |
| **10 GW** | 0.180 | 1.3 | 0.083 | 0.4 | 0.260 | 0.2 |
| **100 GW** | 0.146 | 1.3 | 0.060 | 0.4 | 0.113 | 0.2 |

**Table 5:** Some levelized energy costs (LECs) and energy payback times (EPT) from the EcoFys results.

# Abstract Sheet - Abstract number: 19


| | |
|---|---|
| Author Nam | panzieri, daniele |
| Organisatio | Uiversita' del Piemonte Orientale |
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**SPARK – A Computerised Model for Solar Power Satellite concepts**


The paper presents a computer model to simulate the main technical parameters of different Solar Power Satellite concepts. The aim of the model is to provide a fast easy access for the assessment of technical concepts. The flexible structure of the model allows to arrange different types of orbits as well as different frequencies for the wireless power transmission, including transmission via laser. Different physical configurations can be implemented, allowing comparison between results so as to support the final configuration choice. Dedicated mathematical functions are implemented for specific issues (e.g. aspect linked to the operative temperature). The entire SSP system is included, from the space segment to the ground receiver sites feeding local networks.
The SPARK MODEL program has been developed to evaluate and compute the main characteristics of a Space Solar Power system. The software has been written for a user with some experience in the SSP issues.The input data for the calculation performed by SPARK MODEL program are stored in ASCII files and reflect the present technological knowledge for the various elements (e.g. photovoltaic cells, concentrators etc.). This data format allows the user to keep these files updated with the new technological improvements.
A Graphic User Interfeace (GUI) allows a user friendly approach to the model. The program displays a main window and several dialog windows used to get input parameters and to read the output results of calculation. In almost every window there are two round buttons: clicking on the green one it is possible to proceed with the calculations, with the red one the SPARK MODEL program is quitted. In the input windows, to the right of every filled data, it is possible to see a small grey button with a question mark, clicking on it makes it possible to read a brief description of the command. If an existing project is opened by the user, all the input windows that follow are automatically filled in by the program with the values of the chosen project, but SPARK MODEL program can anyway allow to modify all of them from the keyboard.
The model is developed using the Labview software by National Instruments and STK by Analytical Graphics for evaluating satellite orbital parameters. It is assumed some knowledge on how to use the STK program. The SPARK MODEL program reads the access time, the elevation angle and the distances from two output reports of STK. Some tasks are required to create an output report with these data. The same tasks are listed in the help window that appears when you click on the SELECT ORBIT button.
In order to provide a reference point for a result assessment, some of the test cases have been selected among those presented in the NASA Freshlook study, using as far as known the same input parameters. The test cases that have been selected and "run" with the aim to verify/validate the model behaviour are the following:
Solar Disc delivering 5 GW or 1 GW or 250 MW or 50 MW power to a single site from the orbit GEO, with µwave transmission at a frequency of 5,8 GHz. Sun Tower architecture delivering 1 GW or 250 MW or 50 MW or 10 MW power to a single site from the orbit MEO, with µwave transmission at a frequency of 5,8 GHz. In this case the concentrators are integrated into the cells. Sun Tower architecture delivering 50 MW power to a single site from the orbit LEO sun-synchronous, with µwave transmission at a frequency of 5,8 GHz. The concentrators are integrated into the cells.
The project has been jointly developed by Universita' del Piemonte Orientale and ALENIA Spazio.

# LEGAL ASPECTS OF SOLAR POWER SATELLITES

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*This article is based on a Report made by the Institute of Space and Telecommunications Law for the ESA Advanced Concepts Team.*

The present article tends to give a general overview of the legal principles applicable to solar power satellites – the so-called SPS. The idea to collect solar energy by Earth orbiting satellites, and then to beam this energy to Earth receiver stations in order to convert it to electricity, is not a new one. It has actually been studied since the late 1960's, and several space law eminent authors explored the legal aspects applicable to such possibility, mainly during the 70's and 80's, when first SPS projects arose. Recent technical advances have however conducted space agencies to reconsider SPS projects. The present paper will consequently attempt to come back on these legal aspects by taking the most recent law developments into account. For such purpose, first a general overview of the basic legal principles applicable to SPS will be given (I). Then, the paper will be divided according to the two main phases of a given SPS project – the construction (II), and the operational phase (III).

## I. Issues relating to the basic legal principles applicable to SPS

Since SPS will be developed and operated in outer space, will require orbital positions, and use radio-frequencies, solar and eventually lunar materials, they will be subject to the relevant principles of space law, and firstly to the freedom of outer space principle, as stated by Article I of the Outer Space Treaty[1]. Secondly, and in the light of Article II of the Outer Space Treaty and Article 11 of the Moon Agreement[2], SPS shall not conduct to an appropriation of outer space. The legal notion of appropriation is generally described as constituted of three elements: *usus*, *abusus*, *fructus*. *Usus* refers to the ability to use a resource, *abusus*: the ability to destroy, to give and to sell it, and *fructus*: the ability to harvest its fruits. Applied to SPS, the consequence of the non-appropriation principle is that no use of the resources concerned (solar and/or lunar) shall conduct to its appropriation. This principle might constitute a problematic issue concerning the use of lunar resources by SPS, since such use tends to consume these resources,

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thus prohibiting any subsequent use by other entities – the conditions of *abusus*, as well as *usus* and *abusus* are met and such activity shall therefore be forbidden as an appropriation of lunar resources. SPS operators will therefore have to face such legal constraint in the eventuality of lunar-based SPS projects.

Thirdly, and since SPS involve a use of the radio frequency spectrum, both for telecommunications (the so-called space services) and for energy transmission, they will have to conform with the ITU regime, at least concerning space services. The issue of ITU rules applicability will however appear concerning energy transmission as such, since it does not enter the definition of "telecommunications" as defined by the Union. ITU regulation may nevertheless find application for such uses of the radio frequency spectrum, to the extent that they may cause harmful interference to other existing services. Legal requirements for getting frequencies will therefore also have to be met. On the contrary it must be underlined that ITU is not competent for regulating laser power transmission. Thus laser-based SPS concepts shall be regarded as free from any regulation in terms of frequency allocation.

## II. Legal requirements for SPS construction

Three categories of legal requirements will subsequently be identified as applicable to SPS during their construction phase. The first category is linked to security issues (a), the second one to registration issues (b), and the third one to electromagnetic compatibility matters (c).

### a) Security issues

Article IV of the Outer space treaty forbids the placement in outer space of any object carrying nuclear weapons or any other kind of weapon of mass destruction. Such weapons shall neither be installed on celestial bodies. Therefore, the construction of SPS shall be undertaken so as to avoid their qualification, once constructed, as weapons of mass destruction. Otherwise, their placement into orbit or on celestial bodies, such as the Moon, would be forbidden. Reference can therefore be made to international texts, according to which only three kinds of weapons are currently considered as entering the category of weapons of mass destruction – namely: nuclear, biological, and chemical weapons. While SPS projects here taken as reference are not intended to enter one of these three categories, some SPS concepts are based on laser power transmission. To that extend, and according to the Additional protocol on blinding laser weapons to the Convention on prohibitions or restrictions on the use of certain conventional weapons of 1995[3], SPS shall not be "*specially designed, as their sole combat function, or as one of their combat functions, to cause permanent blindness to unenhanced vision*".

### b) Registration

According to Article VIII of the Outer space treaty, a State on whose registry an object launched into outer space is carried shall retain jurisdiction and control over such an object and over any personnel thereof while in outer space. Applied to SPS, this concretely means that the law of the State of registry will apply to the space object and to the activities of hypothetical personnel being in this object.

ESA ADVANCED CONCEPTS TEAM DESIGN: FABRIZIO L'ABBATE

Particular attention shall therefore be given to registration issues before launching SPS. To that extend, the provisions of the Registration convention[4] shall be observed, which means that the launching State shall in particular furnish to the Secretary-General of the United Nations: the name of the State(s) launching SPS, the appropriate designator of the SPS or its registration number, the date and territory or location of SPS launch, as well as the basic SPS orbital parameters and general functions of SPS.

**c) Electromagnetic compatibility**

It has already been mentioned that SPS imply Earth-based stations in order to collect the solar energy transmitted by the satellites. Should they be territorially subject to European regulations, these ground stations will have to be constructed in accordance with the provisions of the EU Directive on electromagnetic compatibility[5]. This means that they will have to be constructed so that to insure that the electromagnetic disturbance they generate does not exceed a certain level allowing radio and telecommunications equipment to be operated as intended. If applicable to them, SPS constructors will have to design SPS ground stations electrical and electronic elements with due regard to the relevant provisions of the directive.

## III. Legal requirements for the SPS operational phase

As far as the operational phase of SPS is concerned, four issues must be emphasised: jurisdiction and control issues (a), frequency issues (b), environmental issues (c) and liability issues (d).

**a) Issues of Jurisdiction & control**

While in outer space, jurisdiction and control over SPS and personnel thereof will be retained by the State of registry. The law applicable to SPS ground station(s) will be the law of the territory of the State where this (these) station(s) is (are) established. Should a SPS station be based in an extraterritorial zone, such as the high sea, the State retaining jurisdiction and control over this station will be the State of registry of the concerned maritime platform. In all cases, the State retaining jurisdiction on SPS will have to control them and insure, through national authorisations and licences, that SPS conform with the legal principles identified as relevant in this report.

**b) Frequency issues**

Frequencies will have to be allocated to SPS, for both space operation services and power transmission via radiofrequencies. Whereas the frequencies allocated to space operation services should not cause particular problems, due to the fact that it is already foreseen by the ITU Radio regulations, two different possibilities may be studied concerning the frequencies allocated for power transmission. The first solution is to use the bands dedicated by the ITU to the industrial, scientific and medical applications – the so-called ISM. This would present sound interest for SPS operators since according to the Radio regulations, radiocommunication services operating on ISM bands must accept harmful interference that may be caused by other ISM applications. SPS operators would therefore not face the risk of claims due to interference their services might cause. The second solution however foreseeable is to require new frequency bands before the ITU, specially dedicated to SPS, via competent national authorities.

**c) Environmental issues**

Environmental law, and in particular the prevention principle, must be regarded to be applicable to SPS operations as well. According to this principle, States have the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction. SPS operators will indirectly be submitted to this principle of international law, since they will, in particular, have to comply with national legislation stating radiation standards. In most cases, national measures in this field are based on the basis of the recommendations made by the International Commission on Non-Ionizing Radiation Protection (ICNIRP). In the European Union in particular, the Council Recommendation of 12 July 1999[6] strictly reproduces the standards formulated by the ICNIRP.

**d) Liability issues**

As far as liability issues are concerned, the main question relies in the applicability of the space law regime, as provided by the Outer space treaty and the 1972 Liability convention, to damage that could indirectly result from the beam projected on Earth by SPS. This issue, which has not found clear solutions yet, will be very important, since it will determine the regime applicable to SPS for such damage. The general international liability regime might be preferred by SPS operators, but it would be less advantageous for hypothetical victims than the space law regime. Even if this question has not been answered concerning other space applications, the potential damage that SPS could cause, notably on the environment, justify that this problem should be tackled with in a near future.

---

[1] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and other Celestial Bodies, 27 January 1967, 610 *UNTS* 205.

[2] Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, 18 December 1979, 1363 *UNTS* 3.

[3] Additional Protocol to the Convention on Prohibitions and Restrictions on the Use of certain Conventional Weapons which may be deemed to be excessively injurious or to have indiscriminate effects, Vienna, 12 October 1995, CCW/CONF.I/7.

[4] Convention on Registration of Objects Launched into Outer Space, 14 January 1975, 1023 *UNTS* 15.

[5] Council Directive 89/336/EEC of 3 May 1989 on the laws of the Member States relating to electromagnetic compatibility, as amended, *Official Journal* L 139, 23.05.89.

[6] Council Recommendation of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz), 1999/519/EC, *Official Journal* L 199, 30/07/1999 p.0059-0070.

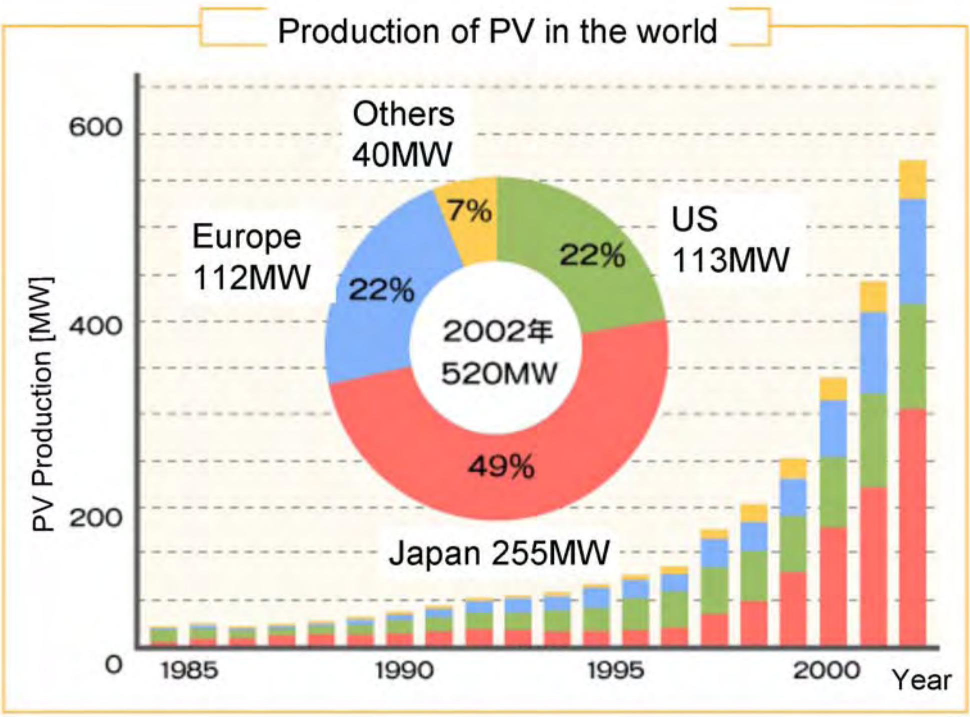
# Peer Review on ESA SPS Study

## Japanese Team


| | |
|---|---|
| Koichi Sakuta | Advanced Industrial Science and Technology (AIST) |
| Yoshiyuki Abe | Advanced Industrial Science and Technology (AIST) |
| Tatsuhito Fujita | JAXA Advanced Mission Research Center |
| Shoichiro Mihara | USEF / Advanced Project Department |
| Nobuyuki Kaya | Kobe University |


## Observers from US at Kobe meeting on 14 October, 2005


| | |
|---|---|
| John C. Mankins | ARTEMIS Innovation Management Solutions LLC |
| Dick M. Dickinson | Off-Earth WPT |
| Joe T. Howell | NASA Marshall Space Flight Center |
| David Smitherman | NASA Marshall Space Flight Center |

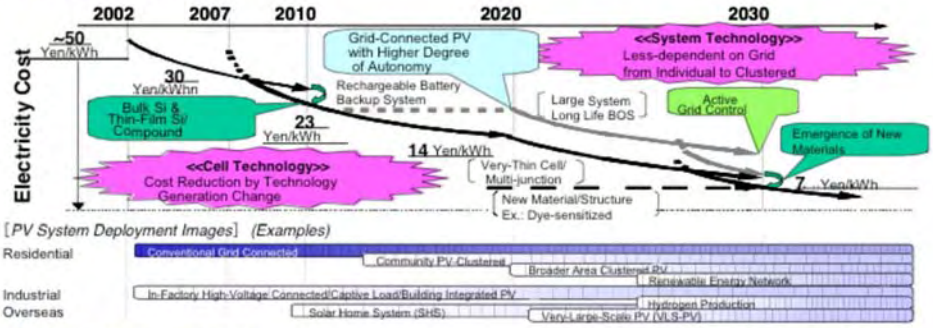
(PV2030)

## Expected Position of PV Power Generation in 2030(1)

**"Unrestricted mass introduction of PV systems"**

- Attain economic efficiency (level of industrial use cost)
- Stand-alone capabilities of PV systems from grid-connected systems and enlargement for various utilization purposes

● **Cost Reduction Scenario**




● **Future PV Power Generation**

| Item | Present Status | | 2030 Status | Notes |
|---|---|---|---|---|
| Generation price | High (twice) | → | Industrial-use level | Low-cost, high-efficiency |
| Reliability of electricity | Reliance on climate | → | Stable power supply | Storage functions, Grid-connected PV with higher degree of autonomy |
| Equipment life | 20 years | → | Over 30 years | Material research, Structural improvement |
| Installation pattern | Individual installation | → | Community-scale/wide-area installation | Community-PV, Active grid control system |
| Necessary area/kW | Large | → | Small | High-efficiency |
| Electricity share | Below 0.1% | → | ~ 10% | Residential, Industrial, Public facilities, Others |
| Plans | ~ | → | Hydrogen production power supply, Very-large- scale PV generation | Unused lands, Very-large-scale systems |

(PV2030)

## Technological Issues of PV Power Generation Toward 2030

**For realization of "unrestricted mass introduction of PV systems"**

**Economic Efficiency Improvement of PV Power Generation**

**(Realization of Electricity cost at 7 yen/W)**

① **Improvement of PV Module Conversion Efficiency**
- Further enlargement of PV applications for housing complexes
- Manufacturing cost reduction

② **Manufacturing Process Revolutions**
- Cost reduction for materials, production, and facilities
- Productivity improvement

③ **Durability Increase**
- Long-lasting PV modules and inverters to match durability of houses
- Electricity cost reduction

**Enlargement of PV System Application Area**

**(formulation of new system configurations that do not overload the grid)**

①**Stand-alone capabilities of PV systems**
Lower effect on power grid; interconnection restriction elimination

②**Active Grid Control Technology**
Formulation of interconnections with other types of energy systems such as via regional energy networks

③**Development of PV systems in response to utilization and purposes**
Mass introduction of PV modules and systems in response to various patterns of use and purposes for factories, building walls, etc.

**Securement of Raw Material Supply**

**(Silicon, Indium, etc. )**

Securement of high-purity silicon feedstock supply and reducing consumption of less common materials (e.g. Indium) to remove obstacles to mass production

**Industrial Infrastructure Enhancement**
- General improvement of installation incentive for users
- Response to overseas markets

(PV2030)

# Targets of PV R&D

**R&D Targets**

**Improvement of economic efficiency:** Realization of similar cost as that for industrial use (7 yen/kWh)
(Milestones) 2010: 23 yen/kWh; 2020: 14 yen/kWh; 2030: <7 yen/kWh

**Enlargement of PV application area:** Cost reduction and stand-alone capabilities of PV systems for inverter and accumulator battery

● Technological Targets Toward 2030

| Item | Present Status | Target by 2010 - 2030 |
|---|---|---|
| Production cost of PV module<br>Conversion-efficiency of PV module | Production: 250 yen/W (2003)<br>Expected development: 14 yen/W (2007) | 100 yen/W (2010)<br>75 yen/W (2020)<br><50 yen/W (2030) |
| Durability of PV module | 20 years | Service life 30 years (2020) |
| Silicon feedstock consumption | 10~13 g/W | 1 g/W (2030) |
| Inverter (power conditioner unit) | ~30,000 yen/kW | 15,000 yen/kW (2020) |
| Accumulator battery | ~10 yen/Wh (for automobile) | 10 yen/Wh (2020)<br>Durability: 10 years |

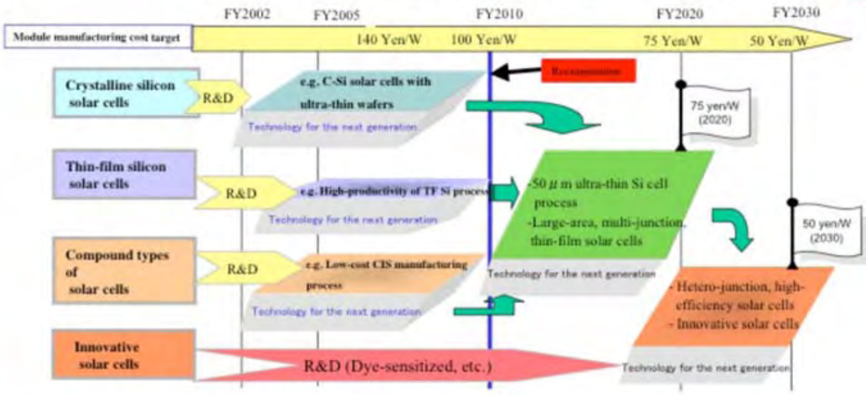
**High Efficiency**

● PV module conversion efficiency targets *(cell efficiency targets)*

| Solar Cell Type | Present Status | Conversion efficiency target (%) | | |
|---|---|---|---|---|
| | | 2010 | 2020 | 2030 |
| Crystalline silicon solar cell | 13~14.8 *(18.4)* | 16 *(20)* | 19 *(25)* | 22 *(25)* |
| Thin-film silicon solar cell | 10 *(14.7)* | 12 *(15)* | 14 *(18)* | 18 *(20)* |
| "CuInSe" solar cell | 10~12 *(18.9)* | 13 *(19)* | 18 *(25)* | 22 *(25)* |
| "III-V" solar cell | Concentrator *(38.9)* | 28 *(40)* | 35 *(45)* | 40 *(50)* |
| Dye-sensitized solar cell | *(10.5)* | 6 *(10)* | 10 *(15)* | 15 *(18)* |

(PV2030)

# Future PV Research and Technological Development (1)




## PV Research and Development (R&D) Scheme

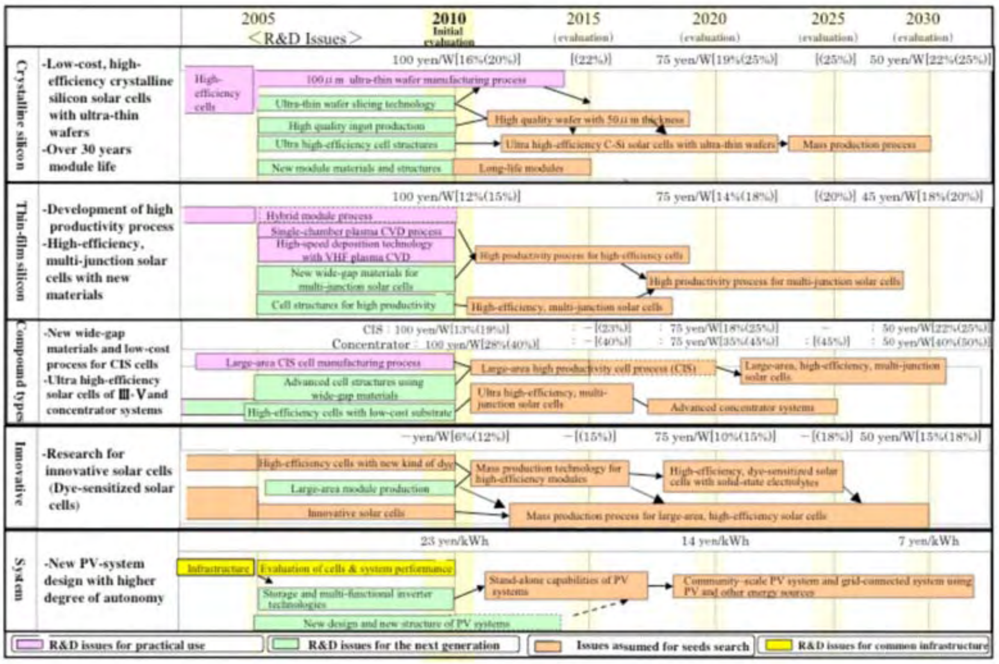
| PV R&D Category | | Concept | Targeted Cost |
|---|---|---|---|
| Development of Fundamental Technology (entrusted research) | Seeds Search | Search to discover technological innovation breakthroughs for PV power generation toward 2030 | 50 Yen/W |
| | Next-Generation R&D | Development of elemental technologies to achieve the 2020 target (Electricity cost: 14 yen/kWh) | 75 Yen/W |
| | R&D for Common Infrastructure | R&D of technologies necessary for all aspects of PV power generation and technologies of a highly public nature | |
| R&D for Practical Use (cost-sharing research) | | R&D for commercialization utilizing the outcomes and for practical application, demonstrative research of novel PV systems, etc. | 100 Yen/W |

Design of Next-Generation R&D utilizing breakthroughs

Earlier practical use of the developed elemental technologies

(PV2030)

## Future PV Research and Technological Development (2)




# R&D Roadmap for PV in Japan (NEDO)

- Cumulative Capacity and Electricity Cost Target:
  - 0.48 GW, 23 yen/kWh in 2010
  - 35 GW, 14 yen/kWh in 2020
  - 102 GW, 7 yen/kWh in 2030
- PV Module Cost and Efficiency Target:
  (a-Si CIS c-Si)
  - 100 yen/W, 12% 13% 16%, in 2010
  - 75 yen/W, 14% 18% 19%, in 2020
  - <50 yen/W, 18% 22% 22%, in 2030
- Other Target:
  - Inverter 15 yen/W, Storage 10 yen/kWh in 2020
  - Module life 30 years in 2020

# Solar Thermal Power Generation in Japan

- Outline
  - Project period: 1977 - 1985
  - Pilot plant completed: 1981
  - Pilot plant operation: 1981 - 1983
  - Plant location: Nio, Kagawa

  - Nominal output power: 1,000 kW x 2 systems (central tower and plane - parabolic)
  - Design insolation: 0.75 kW/m$^2$

# Solar Thermal Power Generation in Japan

## Solar Thermal Power Generation in Japan

- Central tower system (MHI)
  - Collection/Turbine temp.: 249 / 187 °C
  - Heat storage: Steam accumulator
  - Design total efficiency: 0.103
  - Best? measured efficiency: 0.044
    = 0.328 (collection) x 0.134 (generation)
- Plane - parabolic system (Hitach)
  - Collection / Turbine temp: 400 / 346 °C
  - Heat storage: Molten salt
  - Design total efficiency: 0.12

## High Voltage DC Power Lines
### by Tokyo electric company

1. Life
   - Transformer Substation 22 years
   - High voltage Power Line 36 years
2. Construction cost
   - Transformer Substation 2 B$/5GW
   - High voltage Power Line 9 M$/km
3. Maintenance cost
   - Transformer substation 2 B$×2%/year =40 M$/year
   - High Voltage Lines 9 M$/km×2%/y =0.18 M$/km/y

# We-net

WE-NET paper1998 06.3.24 10:37 AM

| Case | Liquid hydrogen transportation system | Methanol transportation system | Ammonia transportation system |
|---|---|---|---|
| Turbine output (MW)<br>Transportation distance (km) | 1,000<br>5,000 | 1,000<br>5,000 | 1,000<br>5,000 |
| Total facility cost ($10^8$ yen) | 7,409 | 4,927 | 5,441 |
| Total annual running cost ($10^8$ yen)<br>(including electric power cost and coal cost) | 1,785<br>(289) | 1,224<br>(251) | 1,450<br>(383) |
| Hydrogen, methanol ammonia(yen/Mcal)<br>(arrival basis) | 10.55 | 5.98 | 6.94 |
| Hydrogen cost (yen/Mcal) | 16.12 | 9.99 | 15.68 |
| Power generation cost (yen/kWh)<br>(transmission end power amount basis) | 32.64 | 24.70<br>(30.83)* | 32.93 |

Note: 1)Hydrogen combustion turbine power generation output : 1,000 MW
2)Hydroelectric power generation cost : 2 yen/kWh (1$ = 120yen)
3)Hydrogen cost is calculated before it is sent to a hydrogen combustion turbine power generation on a basis.

* Parenthesized is the power generation cost including $CO_2$ recovery and processing.

A Peer Review Discussion
of the 2002-2005, the European Space Agency (ESA) Advanced Studies Programme-sponsored studies concerning options for ground solar and space solar power system options for future European energy needs.

# Summary

14 October 2005

# Key Points

- Generally, the ESA study results were viewed as 'excellent' by the participants in the discussion
- There is considerable interest in Japan in alternate energy sources (for example, there has been considerable interest in, and development of solar power roadmaps in Japan)
- Generally (and based on experiments and demonstration plants) it does not appear that large-scale ground solar power stations are viable in Japan (due to weather more than to latitude); this assumption in the ESA studies may not 'generalize' to other regions around the world
- Although there may be some concerns about beam control safety systems, it appears that relatively low power pilot beams should work well for microwave WPT (and perhaps for laser WPT)
- The concept of using space data to better manage ground solar power systems (across a grid) is quite useful
- The use of large scale solar in regions where sandstorms are likely, due to potential damage to the solar arrays
- One might look at the consumption of scarce materials (such as rare earths for multiple junction PV cells) for both ground solar and space solar PV systems.
- Future studies should look more carefully at how ground back-up power for the SSPS constellation is handled (back up power should not be required for the entire power produced by a constellation of systems)

# Introduction

- During 2002-2005, the European Space Agency (ESA) Advanced Studies Programme sponsored a series of studies that examined ground and space solar power system options for future European energy needs.
- In December 2004, ESA and Kobe University agreed on a plan for a Japanese peer review of the ESA study results.
- A meeting was held at Kobe University during October 2005, the purpose of which was to discuss the results of that peer review.
- In addition to the principal participants from ESA and Japan, several observers from the U.S. attended the meeting.
  - Including Mr. John Mankins (who agreed to chair the discussion.)
  - A complete list of attendees is provided on the following pages

## Morning Session – Overview of ESA Studies (1 OF 6)

- Leopold Summerer (LS) presented the background on the ESA SSP/SPS studies, beginning with a review of how this peer review of the ESA studies was organized and the overall schedule.
- ESA is still in the process of 'digesting' the results of the SPS/SSP studies so far.
  - At present, there is some possibility of implementation of additional work during a 'second phase' – including a possible future conference on SPS in Europe as well as discussion of flight demonstration options.
- In general, ESA has concluded that SPS is too immature to be taken over by industry—but it's much too interesting to not continue studies and technology maturation efforts.
  - Also, it appears that there are some cases where a small SPS may be valuable as a substitute to nuclear power for space applications.
- Depending on the results of this review, the 2nd Phase of ESA SPS efforts should start during the first quarter of 2006, with inputs from the European SPS network.
  - These efforts will include the involvement of terrestrial solar power community (reality check, cross-fertilization of ideas, political support), and will look at laser power transmission technology as a topic of particular interest.

## Morning Session – Overview of ESA Studies (2 OF 6)

- LS then presented a brief Overview of ESA Studies, and made an invitation to be critical in comments on the ESA studies.
- Two options were looked at, one at 100 GW, using the Southern European Sunbelt (including Turkey), and one at 150 GW and greater, using North Africa.
- The solar power studies (ground and space) were restricted to the European market, but including North Africa—and the studies were limited to solar power alternatives only (to achieve an apples-to-apples comparison).
- Studies were based on actual projections of base-load and peak power for European markets.
  - Also, the studies were required to assume comparable levels of technology readiness for both ground and space sides—the two sides had to agree on what PV technology is to day (easy to achieve), and what would be available in 2025-2030 (which was more difficult to achieve).
- The technologies considered include PV (as well as the solar thermal trough and solar tower thermal alternatives), energy storage, and other relevant technologies.

# Morning Session – Overview of ESA Studies (3 OF 6)

- There were detailed studies of terrestrial solar power plant options—with detailed assessments of available and acceptable terrain features in North Africa.
  - However, the studies were instructed not to consider risks—particularly related to geopolitical concerns. (Nevertheless, one of the teams did look at the risks of ground versus space solar.)
- A point of some important discussion concerned what kind of cost model to use for these very large systems.
  - The decision was to use for the space and ground PV a learning curve of 80%--with each doubling of production, the cost per KW would be reduced by 20%.
  - For energy storage systems, these were judged to be very mature technologies and only very modest estimated cost reductions were allowed.
- In the analysis of the space solar power, the teams were instructed not to invest time on designed novel SPS concepts (however, some of them did look at new concepts).
  - There was consideration of both microwave WPT and in laser based (IR) WPT.
  - The teams did not consider concepts involving just mirrors in space.

# Morning Session – Overview of ESA Studies (4 OF 6)

- The two ground solar study groups ended with somewhat different results—one a bit more conservative and more centralized, and one more advanced and more distributed.
  - The two space solar power study groups looked at GEO platforms, with quite large power capacities.
- Various options were looked at for energy storage capabilities for the ground solar power systems, including hydro-electric storage (water pumping), and compressed air (data available were poor), and hydrogen storage.
- High voltage DC power transmission and hydrogen (H2) pipeline energy transport worked looked as options.
  - Key issues were identified for the hydrogen option (such as losses in transport… leakage).
  - Integration of hydrogen transport of solar power with ground transportation energy infrastructures were not examined.
- Considerable effort was invested in the modeling of various scenarios.
  - A topic of special importance concerned the modeling of launch costs. (It was very challenging to get to agreement on this among the contractor teams).
  - The decision was to also use a learning curve of 80%, starting with Russian current launch costs of about $10,000 per kilogram.

## Morning Session – Overview of ESA Studies (5 OF 6)

- Another important approach in this study was to normalize all systems analysis to the energy balance: how many kilowatt-hours invested in building and operating the systems compared to how many kilowatt-hours generated by the system.
  - This eliminated suspicions concerning how the detailed cost analyses might be done to calculate Euros per kilowatt-hour.
  - The energy balance calculations were done using data from the European automobile industry.
- The analysis of the energy cost of ETO transport was very interesting, based on the materials (and their energy cost) included in the vehicles.
  - Note (from Joe Howell): it may be useful to take into account the anticipated change in the price of energy during the course of construction and operations. Power purchased now for construction of ground or space systems may be cheaper that power sold later from those systems.
  - Note (from Dick Dickinson): one might look at the consumption of scarce materials (such as rare earths for multiple junction PV cells) for both ground and space PV systems.
- Then, LS presented briefly the principal results of the studies.

## Morning Session – Overview of ESA Studies (6 OF 6)

- As an approach, the teams looked first at the cost of SPS power without launch; then, they established the range (a goal) at which launch costs could enable SPS to be cost competitive.
  - Also, if launch costs are zero and SPS costs are still to high, then there is no viable option.
- In general, the hydrogen energy storage options were far more expensive that the hydro-storage options.
  - Also, in the case of a ground solar power system placed in Egypt, the geography could support the creation of artificial lakes for the purpose of hydro-energy storage.
  - However, there are some residual questions concerning how much water is needed for 100 GW to 150 GW class power systems.
- One of the study teams looked at a very interesting concept of optimizing combinations of ground and space solar power.

## Afternoon Session – Comments and Discussion from Participants (1 OF 5)

- Yoshijuki Abe (YA) of AIST reviewed the ESA study reports concerning space solar power.
  - He noted that the type of analysis done in Japan is somewhat different that in the ESA study (such as the energy payback analysis).
- YA recommended that there be some calculation of the carbon (CO2) costs of alternative energy sources in the future.
  - He also mentioned that there is much more dramatic seasonable fluctuation in the solar insolation in Japan versus Europe. YA offered to provide details of Japan studies at a future time.
- Specific Comments
  - YA mentioned that in the USEF report, there was a projection of 30% conversion efficiency at the PV cell level at the end of life for and SPS in 2030. Also, in the USEF case, the transportation assumptions were (a) from ground to LEO 10,000 yen per kg, and (b) from LEO to GEO at 35,000 yen per kg. For comparison, the current cost for the H-IIA 800,000 yen per kg. The cost per launch is at about $80,000,000 per launch, with a capacity of 3,000 to GEO (which translated to a capacity to LEO of about 10,000).
  - The USEF study assumed reusable launch vehicles, with very high launch rates and much lower launch costs than used in the European study.

## Afternoon Session – Comments and Discussion from Participants (2 OF 5)

- Shoichiro Mihara (SM) of USEF / Advanced Project Department presented some comments on the ESA studies.
  - Not a formal presentation, just some observations.
- SM generally felt that the work done by ESA was quite excellent.
  - He noted that the use of RF SPS may not be a good solution for the southern EU or for North Africa, but this may not be the case for regions often covered by clouds.
  - Hence, USEF is looking at RF SPS has one of the systems for power generation in Japan where it is unrealistic to assume base-load power from (ground) solar power generation.
- SM noted that there are a number of issues for SPS; these include ITU (spectrum allocation) and beam steering.
  - He also noted that space transportation costs are a very serious issue; the USEF approach was to set a very aggressive goal for Earth-to-orbit transportation, such as $100 / kg.
  - In addition, SM noted that space tourism may provide a non-governmental driver for lowering the cost of access to space.
  - He believes that no government will make the investment needed to drive the cost of space launch down just for SPS.

## Afternoon Session – Comments and Discussion from Participants (3 OF 5)

- Dick Dickinson (DD) asked about beam steering issues.
  - SM responded that there may be some concerns about the power level to achieve good beam steering.
  - DD believes that beam steering with low power is not a significant issue.
  - His concerns stemmed rather from his personal experience with military radar applications; he will discuss it further.
- DD and Samuel Kokel (SK) were in agreement that the retrodirective system can satisfy this requirement with only modest power in the uplink pilot beam.
  - This conversation relates to a 'hardware retrodirective system' (with a pilot beam) versus a 'software retrodirective system' which has not pilot beam.
  - N. Kaya (NK) mentioned that in the retrodirective system there is no need for high precision beam pointing control.

## Afternoon Session – Comments and Discussion from Participants (4 OF 5)

- SM has provided some answers to the several specific questions; these are provided in his charts.
  - He noted that there has not been a study in Japan directly comparing space and ground solar power systems.
  - He did note past work in Japan looking at solar thermal—including the pilot plant in the early 80s mentioned previously.
  - However, he expects that as costs for PV come down, people will introduce solar PV on the roofs of their homes.
- SM noted that the latitudes of Japan are actually further south that most of Europe, but that this is not a general perception.
  - The use of ground solar is an issue involving weather, not just latitude.
- He also expressed some concerns about the use of large scale solar in regions where sandstorms are likely
  - He cited the special requirements for cleaning up the arrays after a sand storm.

## Afternoon Session – Comments and Discussion from Participants (5 OF 5)

- LS mentioned that in the next round of ESA studies they plan to examine new strategies of grid management—perhaps using SPS to help with grid management.
- He mentioned the need for better forecasting to improve grid management—and that space-based systems might be able to provide real-time data to make such improvements possible.
  - KS responded that this is the first time that he had heard of such a concept for integrating space data to achieve better grid management.
  - He mentioned that they have used some space photography of clouds. LS will share details of planning for these future studies as they are better defined.
  - This may be a first application of space systems and data to improve the quality and viability of ground solar power systems.

## General Discussion / Concluding Remarks (1 of 2)

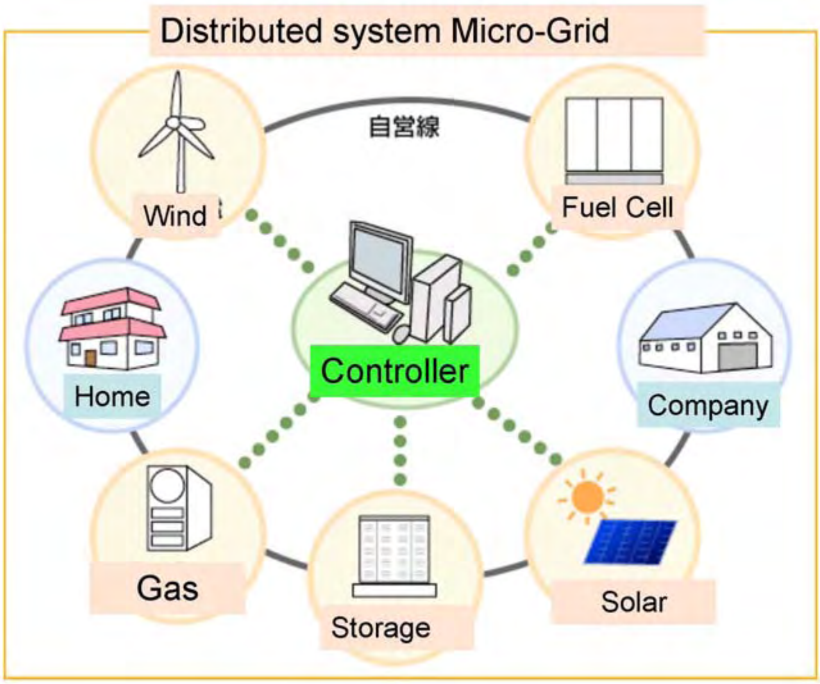
- LS expressed appreciation for the review and for the results presented by the meeting participants.
  - It was essentially what LS desired. He requested that participants in the review provide additional comments to NK.
- DD highlighted the lack of an integrated control architecture for an SPS constellation—including both the SPS themselves as well as the various supporting infrastructures.
  - Also, the integration of SPS with existing power supplies and the grid needs to be looked at more thoroughly.
  - LS noted that ESA assumed that these problems are important—but that first (in the ESA Phase 1 study) they wished to determine whether the systems were viable.
  - LS mentioned that the focus of the next round of studies is likely to focus on large terrestrial solar power and the potential to integrate SSPS power into these infrastructures.

## General Discussion / Concluding Remarks
(2 of 2)

- J. Mankins (JM) mentioned the need in future studies to look more carefully at how ground back-up power for the SSPS constellation is handled.
  - Note: The back up power should not be required for the entire power produced by a constellation of systems. LS will check the assumptions.
- LS restated the need to frame a 'way forward', including closer coordination on some technology development efforts.
- The meeting concluded.

## Questions

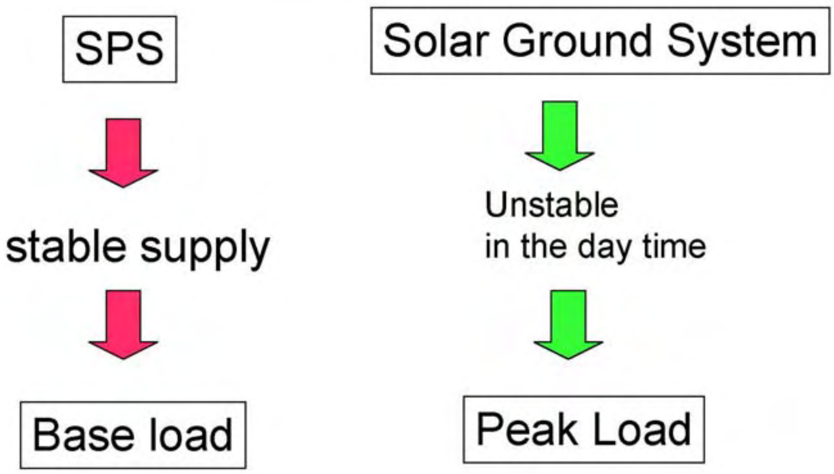
- Why did you compare the SPS just with the ground solar systems?
- Why not with the nuclear power station, LNG, renewable sources of energy, etc?
- Why must the storage systems be examined together with the solar generation systems?




# Distributed Energy System

- No transmission lines
- High efficiency
- Use of exhausted heat
- Small scale accidents
- Stable supply

# Characteristics of power Generation




- Receiving sites should be close to the consumers.
  (Microwave is better than Laser for Ground system)
- Storage system should be independently examined.
  (Use of other power plants, LNG et al.)
- SPS should be independent from the ground solar system.
  (No merits by combining SPS with Ground)
- Is it possible to simultaneously use the PV for SPS and Ground Use?

## Suggestions for Phase II

1. First, technologies development by universities (Cheap, new ideas, education)
2. Competitions encourages activities on the developments.
3. Business models for the developed many technologies.

A Peer Review Discussion
of the 2002-2005, the European Space Agency (ESA) Advanced Studies Programme-sponsored studies concerning options for ground solar and space solar power system options for future European energy needs.

## Selected Observations & Thoughts for Future Studies

24 March 2006

## Some Observations & Thoughts (1 of 4)

- Generally, the methodology and results of the initial ESA GSP-SSP Comparative study are quite good
- The decision was to use for the space and ground PV a learning curve of 80%; As a consequence, with each doubling of production, the cost per KW would be reduced by 20%.). A learning curve of 80% is probably too low (based on several production examples (such as ET, GPS, Iridium, etc.)
- For exceptionally large, ground-based solar power systems, the effects of the environment could be examined more carefully (e.g., abrasion of the cover glass by sandstorms)
- The ground rules of the study excluded 'geo-political' considerations; this ground rule limits the degree to which risk-based analysis could be used (i.e., expectation values for key results, versus simple calculations)

## Some Observations & Thoughts (2 of 4)

ARCHITECTURE-RELATED

- Some consideration should be given to the use distributed architectures, rather than centralized cases, particularly for the ground solar power systems (roof top scale) and space solar power (100 MW to 1 GW ground receiver scale)
- The possible use of off-shore platforms for power reception might be a topic for additional study (based on the large number of off-shore oil platforms that will be decommissioned during the coming decades)
- Future studies should look more carefully at how ground back-up power for the SSPS constellation is handled; as noted, backup power should not be required for the entire power produced by a constellation of systems
- The possible application of SSP in 'load leveling' across a continental-scale grid might be given greater consideration (e.g., following peak loads during the diurnal cycle)

## Some Observations & Thoughts (3 of 4)

SSP/GSP PROGRAMMATIC-RELATED

- Some more detailed consideration of the 'programmatic role' of space applications of SSP technologies should be considered (e.g., in financing systems developments "off the books")
  - Including robotic and human missions, and prospective space utilization other than SPS
- A separate parametric consideration might be given to the question of 'fuels' for transportation in both SSP and GSP cases (particularly concerning 'off peak' hours when the system generate more power than is needed for the 'grid')
- A parametic consideration of alternative learning curves ('goal setting') might be useful
  - Including learning curves greater than and less than 80%

## Some Observations & Thoughts (4 of 4)

STUDY METHODOLOGY-RELATED

- Future studies might consider the use of additional workshops / working meetings with broader engagement--perhaps with one purpose being to set additional 'functional goals' for major system elements and technologies
- Future studies should consider the addition of 'risk--perhaps based on 'geo-political' considerations--to enable the use of Monte Carlo type simulations and/or the calculation of expectation values for key results
- A parametic consideration of alternative learning curves ('goal setting') might be useful (greater than / less than 80%)
- Future efforts might consider beginning the definition of 'roadmaps' for relevant SSP systems and technologies—focusing (per NRC study results) on interim applications that are 'self-justfiying'