IAC-02-R.1.03

Space Solar Energy : A Challenge for the European (and International) Community

Iskender GÖKALP[1]
LCSR-EPEE-CNRS, Orléans cedex 45071, France, gokalp@cnrs-orleans.fr

Max CALABRO[2], Hervé HOLLANDERS[3]
EADS-LV, Les Mureaux cedex 78133, France

Lucien DESCHAMPS[4]
Électricité de France, Division Recherche et Développement/PROSPECTIVE 2100, France

Abstract

The Space Solar Energy (SSE) project is now turning into reality in the agenda of several organisms, such as NASA in the USA and METI in Japan. Europe is still running behind for this challenging long term science and technology development activity, which may have crucial global consequences on space transportation, and, beyond, on the life on Earth. The main goal of this paper is to draw the attention of European organisms and companies active in the field of space transportation on this topic, and to propose an R&D roadmap to support multidisciplinary system studies in order to give an opportunity for the European Community to demonstrate its ability to put large SSE systems in orbit.

1. Introduction

The future of the energy question on our planet raises two interconnected challenges. First, the main terrestrial energy source is still today based on fossil fuels, which are limited in the long term: they will be exhausted in the future. Second, the continuation of their intensive use with an ever increasing pace (because of the energy needs of the increasing world population) will perturb the Earth climatic equilibrium by the injection of significant amounts of carbon dioxide into its atmosphere and therefore increasing the Earth global warming by the way of greenhouse effect due to the presence of CO2. These two challenges are today well captured by the scientific and governmental bodies.

However, no global action, (i.e. at the Earth scale) is yet planned to propose and develop a safe and abundant, i.e. sustainable, new energy source, so as to allow emerging nations to satisfy their increasing energy needs and the developed nations to decrease their CO2 emissions.

Today, to satisfy their energy consumption, the world population of 6 billions needs approximately 9 Gtep per annum (1 tep = 11 MWh). It should be noted that nations are not equal and whereas emerging nations consume only about 0.75 tep per capita per annum, developed nations consume 4.7 tep per capita per annum. In 2050, the world population is expected to reach 8 to 10 billions of inhabitants. It is also expected that developed nations population will stay stable around 1.15 billions (Boisson, 1998; Bauquis, 2001).

---

[1] *Director of the Research Federation "Energetic, Propulsion, Space, Environment -EPEE-CNRS"*
[2] *Senior Executive, System Studies and Test Directorate, EADS Launch Vehicles*
[3] *Deputy Vice President, Innovation, Research Directorate, EADS Launch Vehicles*
[4] *General Secretary, Prospective2100, Meudon cédex 92195, France*

Energy consumption reduction is not expected for developing countries, even if significant energy savings are possible. It is expected that their energy consumption may reach 2 or 3 tep per capita per annum. In 2050, the global energy need may then well reach 25 to 30 Gtep per annum.

For 2050, the oil production predictions are about 3.5 Gtep, those for natural gas 4.5 Gtep and also 4.5 Gtep for coal (Bauquis, 2001). Therefore, for the second half of the 21st century, the energy deficit to be filled in by non-fossil energy sources could well be about 17.5 Gtep. It is also predicted that by 2050, renewable energy sources such as biomass, wind energy or conventional ground based solar cells would contribute to this deficit with only limited capacities. Even if desert areas are chosen for Earth based solar energy production, the transport of power on very long distances (over several 1000 km) by conventional grid systems is a challenge today (but see Hashimoto et al 2001, for a original scenario).

Several previous studies have shown that various technical possibilities already exist to globally tackle the energy and CO2 emission problem by using solar energy at a large scale. In this paper, we shall favor space based solar energy scenarios; it is however obvious that mixed scenarios should also be envisaged seriously.

For the time being, we suggest to envisage the space solar energy scenario (coupled with Earth based solar energy ones) as enlarging seriously the spectrum of potential global solutions (another one being obviously the nuclear fusion) for the world energy problem knocking at the door for the second half of this century.

It seems also clear that the future global energy scenarios should envisage the simultaneous production of various forms of energy carriers, such as electricity, hydrogen and heat, by developing poly-generation approaches.

Capturing the solar energy in space and transporting it to the Earth has been imagined by some visionaries since the early decades of the XXth century. Konstantin Eduardovich Tsiolkovsky, one of the founding fathers of the astronautics and of the space age, was already suggesting to capture the space solar energy (SSE) for Earth use (Tsiolkovsky, 1925, in Deschamps, 2000). This vision was turned into a concrete proposal by Peter Glaser at the end of the American Apollo Lunar Programme (Glaser, 1968). Since then, SSE is investigated as a global solution of clean and abundant energy production for our planet by using its unique infinite source of energy, i.e. the Sun. Very large scale solar energy collection platforms (gigawatt electric power class) would transform solar energy into electricity by the photovoltaic effect, and then into (for example) microwaves in order to beam it down to the Earth.

Studies conducted during the 1990ies within the NASA SERT program, and also by NASDA and NAL with METI funds, have identified several scientific, technical and environmental problems to be considered and solved before the SSE project gains in international and public support (Mankins, 2001; Mori et al, 2001). One key issue is obviously the construction of very large solar energy collection orbital structures (several square km) and their maintenance.

Economic feasibility analyses of the SSE project point out the space transportation cost as the main cost element. They show that the space transportation cost should be reduced drastically compared to today's costs to render economically viable the SSE project (Charania et al., 2000; Greenberg, 2000). However, additional SSE cost scenarios taking into account the probable CO2 emission penalties to be internationally introduced in the near future should also be considered.

Furthermore, the SSE project itself, with its considerable need for frequent launches may induce a launch cost reducing effect by the increased market size and the effect of serial production, and initiating a virtual circle both for space transportation industry, terrestrial energy industry and utilities and, ultimately, for the safe future of mankind on Earth.

Finally, Space Solar Energy can be used not only to provide energy to the Earth and for the propulsion of space vehicles, but for other various applications. Some of them have already been investigated in the literature, such as:

- Distribution of energy to satellites already on orbit, thus reducing the solar panel surface and mass and also onboard propellant mass (Grey and Deschamps, 1989; Mullins, 2000).
- Distribution of energy to "sky stations" (large propelled, 30 km altitude stationary ballons for telecommunications)

- Regulation or control of climatic extremes on Earth, such hurricanes (Eastlund and Jenkins, 2000)
- Destruction of orbital debris by SSE powered laser beams (Grey, 2001).
- Orbital control and power supply for free-flyer platforms for scientific experiments or material processing necessitating very low microgravity levels, such as crystal growth (Pignolet et al., 2000).

The European Union and more generally the European Community should not be absent in this long term effort which might have crucial consequences on the life on Earth, and especially on the eve of the 6th European Framework Program, where, among others, clean energy and control of climatic change for a sustainable development and Aeronautics and Space, appear as top R&D priorities.

This paper addresses some implications of preliminary R&D and demonstration projects on the assessment of the feasibility of the global SSE project, and also on other space activities.

2. Problematic of a Solar Space Energy Program

The technical challenges of the global SSE project can be summarized around three items:

- the minimal cost of, for instance, a MW solar energy power unit in space, where the driver is obviously the mass per MW. This cost will impact the architecture of SSE unit, its construction, operation and maintenance strategies.
- the selection of the energy collection and power transmission technologies. For power transmission, laser or microwave beams, or their combination associated with relays, have to be considered. In this selection, the choice of the operating orbit or site has a strong impact, since longer is the distance for transmission of energy, more efficient seams the laser technology.
- the advances in solving key technology problems through appropriate R&D programs, especially for the overall effectiveness of the SSE system.

Space Solar Energy: How and Where ?

To insure the Earth power prosperity, by continuously providing 20 TW to 8 to 10 billion people in 2050 may represent more than 300 million tons on-orbit and 330 000 km2 of solar collectors and whatever the chosen scenario, a dramatic increase of the launch rates. As a consequence, the use of exclusively “green propellants” seem mandatory.

To determine where is the optimal position in space of electricity or power production units, multidisciplinary system studies are mandatory. They have to take into account the major driver, which is the total cost of a kW produced and distributed to the end user, on Earth or Space, including the Earth to orbit transportation. For this last issue, the cost drivers will be:

- The choice of the orbit (the transportation cost is lower for lower orbits)
- The number of SSE units and relay stations put into orbit
- The intrinsic SSE system cost that depends on its production location : unit module produced and assembled on Earth versus a partial production on the Earth or on the Moon and in space final manufacturing and assembly
- The system mass and compactness.
- The cost of the maintenance

For these last items, the global efficiency and the way to obtain it are also major drivers. For example, if laser technology systems are available and usable for transmission of energy with a not too low efficiency, it will lead to a dramatic decrease of the collection and optical/antenna surfaces and as a consequence to a decrease of the launching costs.

Recent studies (AIAA, 2000) show that improvements in high power laser performances are achievable in the near term, reducing the overall on-board mass to more commonly known levels.

All these considerations have a direct impact on the number of launches and on the design of the dedicated launch vehicle, that have to be most probably a fully reusable RLV or a very low cost expendable launcher. Consequently, they emphasize the urgent need to start system studies of such space infrastructures.

One major constraint in the location of such large space structures remains the possible artificial debris hazards and those due to meteorite storms. A large number of SPS may generate sufficient debris to make the access to both GEO and deep space very hazardous (Criswell, 2001).

Several authors have studied the advantages and disadvantages of various orbit choices. Such analyses have prompted some designers to choose the localization of the orbit not lower than the geo-stationary orbit.

However, a special attention should be paid to the Sun Synchronous Orbit (SSO) which benefits of a quite easy accessibility, as well for implementation of SSE production units as for maintenance. Unfortunately, such an orbit could also present debris hazards that have to be quantified.

Since geo-stationary satellites orbit at such a high altitude, the amount of time that they spend in the Earth's shadow is minimal. Interruptions would cause a total power outage of about 1%. They could beam directly and (almost) continuously the energy to off-shore platforms, desert regions equipped with reception antennae or rectennae. The GEO position allows indeed a single satellite to supply power to a given receiving station on Earth.

But a major question still is : What is the debris generation risk and do we have to preserve from debris this orbit dedicated to telecommunication satellites ? And therefore do we have to use orbits beyond GEO such as L1 Earth-Moon halo orbit or the surface of the Moon ?

10 to 20 pairs of bases on opposite limbs of the Moon would allow to continuously beam down to a given point of the Earth, over the course of a lunar month except during a full lunar eclipse, which occurs approximately once a year and lasts less than 3 hours (Criswell, 1998; 2001; 2002).

Some projects also suggest to take advantage of lunar soil to extract materials and produce in situ components of SPS, in order to reduce space transportation of human teams or robots and of high added value components and also to allow an easier maintenance of the SSE system.

Other solutions would be to combine Solar Power Systems (production unit and associated relays) whatever their orbit could be:

- with an important number of high stationary atmospheric altitude platforms or balloons (SHARP, Sky Station or others). The altitude have to be high enough to be over the clouds and the location close to the final consumers like large cities. These platforms receive in that case laser beamed energy from a far SPS or reflector (mandatory in case of on Moon production) and use microwave or cables for transmission to the Earth. In case of stationary balloons at roughly 5 km altitude, if authorized, a breakthrough should be possible with the use of carbon nano- tubes.
- with on-ground existing infrastructures: if very large collection of solar energy is done in desert regions of Earth, not too much subject to weather disturbances, the efficiency of such units could be at least multiplied by two, through an illumination by a laser beam during mainly the night and why not also during the day, the efficiency of solar cells being higher with coherent light.

It appears therefore that a wide range of alternative systems are possible. Considering that the cost to first power is a driver for implementing later SPS systems, it can be suggested that a practical SPS architecture may evolve as follows, over time :

A) For near term system level demonstrations, a system in a low-altitude sun-synchronous orbit appears to offer the lowest cost, with a reasonable potential for commercial use.

B) For moderate-scale, local power generation in the next century, larger GEO systems would seem to be the most practical and have to be considered.

C) For very large-scale, SSE systems for future generations, lunar surface based systems appear to have the greatest potential.

With such a phased implementation approach, Space Solar Energy projects may grow from initial, affordable system demonstrations to interim commercial applications, and eventually to achieve low-cost global energy systems.

How to produce , how to transmit ?

To select the power production mode from sunlight and its transmission mode, one criterion could be the overall efficiency. Microwave transmission requires electric power. NASA studies show a competition between photovoltaic production and thermo-generator production based on Stirling or Brayton cycle engines. These last solutions seem more competitive. Boeing has investigated four generic categories of solar power production options for next generation 40 – 100 kilowatt-electric applications where weights and costs are summed to the entire

power generation system level, not just the receiver.
In the case of the triple junction photovoltaic system, the specific mass under consideration is that of the photovoltaic panels, backup structures, electrical cross-connections within the panels, pointing and steering systems, deployable mirror structures, power storage (for eclipse periods), power management (voltage stabilization and conversion, if required), and power distribution systems. Dynamic engines require somewhat different systems but basically all the same functions for the given application. The Stirling and Triple Junction photovoltaic systems appear to be the most promising at this power level.

Nevertheless non rigid solar cells are under development for balloons (Sky Station) with expected efficiencies up to 25% over a thirty years life.

When the problem of producing electricity will be solved, its transmission will remain to be considered, if the produced electricity is not used in situ. One has therefore to consider:
- Conversion to microwave (in the range of 2.45 - 5.8 GHz or higher) for a transmission through the Earth atmosphere mainly,
- Conversion to laser beam for in-space transmission.

The option of direct light-pumped laser power transmission will be well suited for in-space energy transmission (e.g. to solar sails, laser thermal or laser electric transfer stages, to Earth satellites, to the Moon, to some km altitude Earth stations).

In the case of power transmission to Earth, use of rectennas allows the hope of conversion - in a ground station close to final consumers – from microwaves to electricity with good efficiencies (up to 80%).

Wireless Power Transmission (WPT) involves converting solar light into electrical energy and then into microwaves or laser beam at a transmitting station (Dickinson, 2001; Kaya et al., 2001). Then, depending on the final use, it involves:
- converting again the power back into electricity at a receiving station for Earth or Moon power supply or for electric space propulsion (Hall thrusters, XIPS, VASMIR) of a vehicle,
- using directly the laser light for propulsion in case of Solar Sails or Solar Thermal Stages.

The two different types of transmission, i.e. Microwaves of different wavelengths or Laser beams, have several advantages and drawbacks, which are here analyzed through a system approach. In this approach, one has to minimize the on-board mass, i.e. the size of optics / antennas and the mass of energy collection / conversion system.

Concerning the size of energy collectors and transmitters, with the same efficiencies and the same maturity than microwaves, laser transmission in space will be far more interesting than microwaves (Toussaint, 1992). In fact, diffraction of microwaves being much higher than for laser transmission, this leads to heavier emission and reception systems. This results from the relative product of emission surface multiplied by reception surfaces, at least 10 million times lower.

However, microwaves consist of long wavelength, low energy electromagnetic radiation. Therefore, they do not interact with the atmosphere as much as the shorter wavelength, higher energy radiation. They can therefore be used more efficiently to transmit energy from solar power systems or intermediary relays back to the Earth.

Nevertheless, the prospects are dim to obtain international regulatory approval of a high power transmission system before guaranteeing zero possibility of interference with communication satellites and position location systems (AIAA, 2000; Salin, 2001).

Concerning laser beam systems, a great deal of technologies should be developed to be able to obtain:
- reasonable mass and size of the on-board high power laser generator, taking into account the dissipation of the residual energy
- an efficiency of the energy conversion greater than few per cents
- deployable optics not limited by their thermal behavior (maximum power density) that may limit their size reduction
- long range Acquisition Pointing and Tracking system (Ninneman et al., 2001).

Furthermore, the use of high power lasers in space should be submitted to international space law regulation.

Since many improvements should be expected in the mean time through research programs on both microwave and laser technologies, one has to avoid a hasty choice which could conduct to a non efficient solution. However, there is no doubt that the high power laser option for transmission needs to be extensively studied in order to put it at an acceptable level of efficiency.

Converting electricity into microwaves can be done using a TOP, Klystrons, Magnetrons or Gyrotrons. The efficiencies today obtained with magnetrons reach 70% at 2.45 GHz. Gyrotrons able to operate at millimetric wavelengths are under development and efficiencies around 30% are obtained.

Reception and conversion into electric power on ground should also be treated in detail. The ground receiver, using laser beams could be photovoltaic arrays. However, due to the narrow spectrum of laser beams, conversion efficiency can be significantly higher (about 60%).

For microwaves, due to the large distance between the Earth and power satellites, a large rectifying antenna (Rectenna) would have to be built, typically several kilometres of diameter. Low intensity microwave radiation has proven to be relatively harmless to humans. However, it could be very dangerous at high intensities. So, the beam of microwave intensity must be shaped so that to fall off in intensity very rapidly at short distances from the rectifying antennas. Off-shore reception stations have been generally considered as good locations to be close to electric consumer zones and to avoid any safety problems and a large waste of real estate.

Converting sunlight into electricity and then into laser is another option. According to (AIAA, 2000), the overall efficiency (sunlight into DC grid power out) is estimated today to be 6.2% and 15% would be a reasonable goal.

Converting sunlight directly into laser is controversial. Due to a very low measured overall efficiency, without major improvements or technological breakthrough, the mass of the space segment would therefore be prohibitive (AIAA, 2000), but according to (NASA, 1997), a breakthrough seems possible.

Laser for Propulsion

Three basic systems fall into this category: solar sails, solar electric and solar thermal propulsion. The high thrust of solar thermal propulsion has led to consider it for missions from LEO to GEO that are time critical, such as commercial and military satellite delivery.

For operations higher above the Earth, where acceleration is not as critical, or where mission duration is not a factor (such as planetary missions) solar electric concepts may offer significant benefits in overall system mass and propellant use. For applications such as commercial communication satellites that already dictate the need for a large electrical energy generation system, the addition of electric propulsion systems, either Hall or XIPS, are very weight and cost effective for low thrust station keeping purposes and final orbit placement.

3. Technological and economical key issues related to Space Solar Energy

As already considered in the NASA report (AIAA 2000) one has to address the following topics:

- Space transportation : Earth to orbit ? orbit transfer ? station keeping
- Power generation and distribution : energy collection and conversion, energy storage, onboard power management and distribution
- Power transmission : wire to wireless conversion and transmission; wireless to wire conversion; beam control and stabilization
- Structures
- Operations : fabrication and assembly; on-orbit operations, maintenance and repairs
- Housekeeping services : guidance, navigation and control; thermal control; communications and data handling.

4. System Requirements and a Proposal of an R&D Program

Several specific technologies for which system requirements would need to be formulated have been identified in (AIAA, 2000). These key issues need to be developed in appropriate R&D programs, in which flight demonstrations will also be performed in order to address and solve the critical problems.

From our concern, R&D priorities will be oriented towards two main topics :

- The problem of solar energy conversion, i.e. power generation, distribution and transmission. For space lasers, Ninnemann (2001) describes R&D needs.
- Propulsion by high power laser and the integration of this propulsion mode into stages of space vehicles.

These topics will be investigated through both a basic research R&D program and specific R&D programs, such as :

- Laser propulsion program
- Space microwave generator program
- Space Laser program.

Some preliminary identified items are therefore the following:

- Microwave-space plasma interaction
- Solar cells with high efficiencies
- Rigid, stacked solar cells to capture multiple wavelengths (efficiency over 30%)
- Thin films (efficiency over 25%)
- High frequency microwave generators
- High frequency rectennae
- Large deployable structures
- New technologies for laser lens
- Magnetrons, gyrotrons and others
- Supra conductors at high temperatures
- Cooling techniques
- Solid state, multi -channel laser with direct solar pumping
- Photovoltaic receiver-converter for laser beam
- Laser-Earth atmosphere interaction
- Diffraction-limited laser beams (phase conjugation techniques, phase conjugating mirrors PCM)

Validation and qualification of these key technologies need the development of small-scale demonstrators, which will be scheduled in phase with the major advances of technology research.

Space Solar Energy roadmap

This roadmap will be constituted with the previous R&D programs to be developed from now to Year 2040, coupled with system studies which may drive the reflection on technology demonstrators (see Fig. 1). On-ground and In-flight validations will be conducted during the same period. For the ground validation, they will include:

- conversion of received energy to laser beam and microwaves
- atmospheric effects such as absorption
- system safety demonstration
- overall validation of SSE units
- Laser propulsion development

For the in-space validation, they will include:

- Choice of space localization (LEO, L1 Earth-Moon, L1 Earth-Sun or Moon) and demonstration of the capacity to carry and assembly there an SSE unit.
- Gradual power increase of the SSE unit.
- In-space demonstration of a beamed laser Space Tug (or implementation of an intermediate step with microwave energy transmission)
- On-board power supply experiments with solar panels, laser beam devices, microwave generators, rectennae, hydrogen tanks, electric power supplies, robotics, etc.

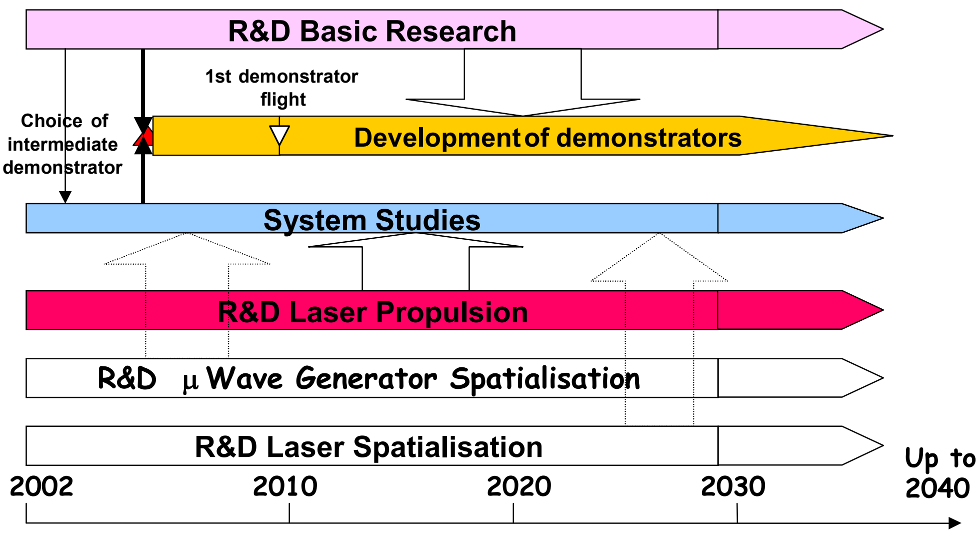

Fig. 1. Space Solar Energy Roadmap

Fig. 2 shows a sketch of key technology demonstration logic, which consists of a stepwise approach, including 5 to 6 steps of in-flight validations after the mandatory ground step one:

1. Ground qualification (1 MW, 10 MW…).
2. LEO launch and 1st in-orbit assembly of SSE devices if needed, 1st tests of transmission and reception of energy on the Earth.
3. Transmission of energy from a GEO satellite to a LEO one.
4. GEO or Moon station launch and tests of several energy transmissions and receptions by means of laser or microwaves either directly to the Earth or by the way of an intermediate low altitude station.
5. Transmission of energy to a vehicle or a satellite (arc jet, electrical, MHD, solar sail propulsion) :
   - To a Space Tug able to transport SSE unit elements from LEO to the final chosen orbit
   - To an interplanetary vehicle (lightest solutions for the vehicle would use laser beamed propulsion).
6. In flight demonstration of a high thrust OTV (several Newtons laser electric or others).

The launches of the space demonstrators should be envisaged with the existing ARIANE 5 launcher, before a new launcher appears in the mean or long term.

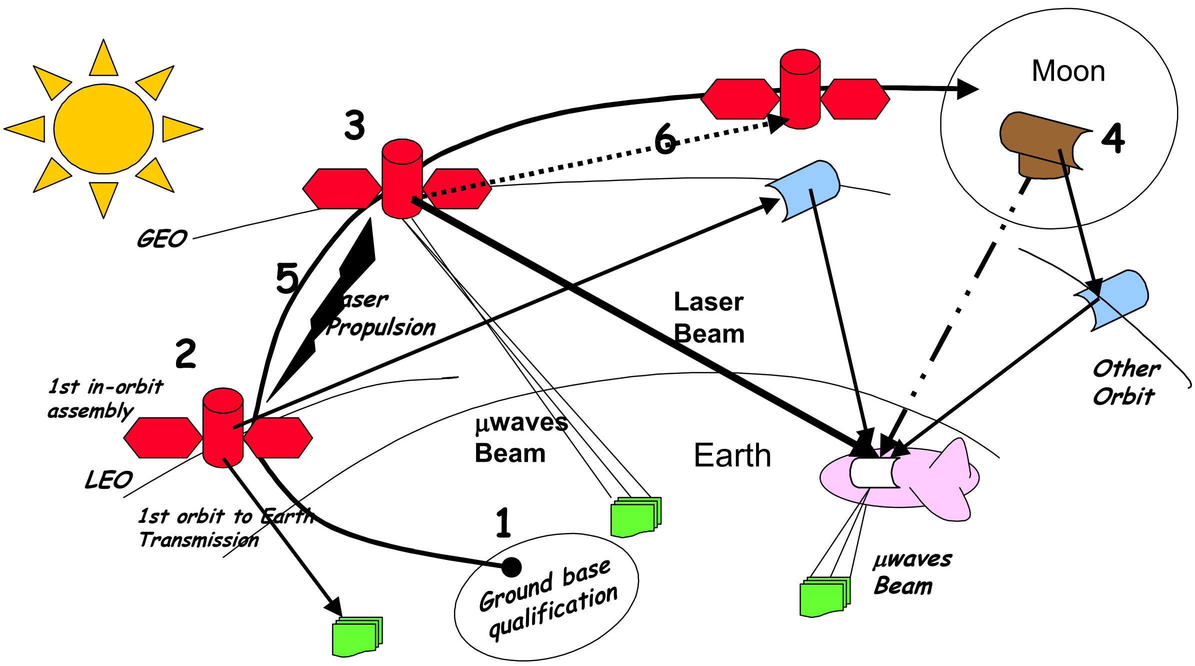

Fig. 2 Stepwise Logic of Qualification

Collaboration framework

To implement the proposed R&D roadmap and the stepwise logic of qualification, we propose to assemble an integrated consortium which should advance knowledge on enabling technologies for Space Solar Energy. The best context, in Europe, to start such a consortium could well be the 6th Framework Program (FP) of the European Commission, for various reasons.

First, the 6th FP lists the long term energy issue and the control of the climate change as one of its top priorities. Integrated programs within this priority area has a very high relevance. In addition, another top priority area of the 6th FP is Aeronautics and Space, mostly related to the use of space for advanced telecommunications, Earth observation, global positioning etc. The SSE project concerns directly both of these priorities.

Second, a project such as SSE cannot be but international, and in the European context, it should involve several European partners. The consortium should therefore be multi-expertise, multi-nation and multi-purpose.

The multi-expertise character of the consortium is mandatory with regards to the variety of scientific and technological problems to be solved. For example, space propulsion and transportation specialists should work in close connection with photovoltaic, power transmission, microwave, and laser experts. Economy, finance and international law specialists should also join the consortium together with space science experts.

The multi-national character of the consortium is related both to the above multi-expertise character and to the necessity to strengthen European collaboration on key areas such as access to space resources and safety and availability of energy resources for Europeans. For example, in the space transportation area, European forces on space propulsion and system integration should work closely together, obviously also with the European Space Agency. In a similar vein, various European energy utilities should be invited to join the consortium.

The multi-purpose character of the consortium is related to its long term aspect and to the fact that the SSE project may contribute to solve several type of problems, ranging from the energy problem to cheap access to space, use of space resources and also several unexpected uses of technologies to be developed for SSE.

Obviously, the European character of the proposed SSE project does not mean that SSE will be an exclusively European achievement. By definition SSE is a global therefore Earth wise project. The aim of the proposed European SSE consortium and project is simply to consolidate the European efforts on this topic to enable them to collaborate more readily and efficiently at the global level. On the other hand, from the beginning of the project, Russian and other Eastern European countries should be strongly involved within the SSE European Integrated Project.

Only an integrated approach at the European level, and using the opportunities provided by the 6th Framework Program, may help to give birth to the project "Energy, Space, Solar Power, Environment: a Research Association for a New Society", that is **ESSPERANS ©**.

5. Conclusions

Solar Power Systems for Space Solar Energy generation constitute a promising technological project that could lead to a global solution of both Terrestrial energy and climate change problems in the long run. This technology has also a critical impact on space transportation per se, to enable the access to various other space resources.

The widespread implementation of Space Solar Energy systems would mean that a boundless source of clean energy could be used to replace the finite fossil fuels in due time and to stop their harmful effects of the Earth environment and climate.

New developments in solar energy research and technology have led to considerable progress in the recent years, in terms of photovoltaic conversion efficiency, for example. Efficiency in solar power conversion technology is indeed rapidly increasing to the point that it is now feasible to use solar technology on a large scale to replace other types of power plants. This efficiency would largely increase if the plants were implemented in space instead of on Earth.

Similarly, other connected areas should also experience strong progress in order to advance knowledge to enable technological development for the realization of the Space Solar Energy project.

The European Community should not be absent in this long term challenge and should be able to demonstrate its ability to put in orbit such large SSE systems.

To achieve this objective, a strong and long term R&D effort should be devoted to support Industries and Research Centers, i.e. on extended multidisciplinary system studies together with basic and applied R&D programs, especially in the field of laser technologies for space energy transportation and propulsion. The Consortium **ESSPERANS**© is aiming at contributing to this objective.

6. References

AIAA (2000) Report to MFSC/National Aeronautics and Space Administration, AIAA "Assessment of Space Solar Power Concepts", NASA Grant NAG8-1619, October 31, 2000.

Bauquis, P-R. (2001) Besoins et approviosionnements en énergie à l'horizon 2050, Institut Français de l'Energie. Enerpresse No 7882 and 7883.

Boisson, P. (1998) Energie 2010 – 2020. Rapport final – Commissariat Général du Plan, France.

Charania, A. et al. (2000), "Unified economic view of Space Solar Power", IAF-00-R.1.06, 51st International Astronautical Congress, 2-6 October 2000, Rio de Janeiro.

Criswell, David R. (2002),” Solar power via the Moon”. The Industrial Physicist, April/May 2002,
Criswell, David R. (1998),” Solar power system based on the Moon”, Chapter 4.11, pp. 599-621, in Solar Power Satellites: A Space Energy System for Earth, Peter E.Glaser, Frank P. Davidson, and Katinka Csigi, editors; Praxis Publishing Ltd., Chichester England, 1998.
Criswell, D.R., (2001), “Characteristics of commercial power systems to support a prosperous global economy”, IAF-01-R.3.08, 52nd International Astronautical Congress, 1-5 Octobre 2001, Toulouse.
Deschamps, L. (2000) Les centrales solaires spatiales des années 1900 à demain. Revue AHEF, No 35, pp. 79-100.
Dickinson, R. (2001), “Wireless power transmission technology: basics, frequency, choices and issues”, 1AA-01-IAA-7.1.02, 52nd International Astronautical Congress, 1-5 Octobre 2001, Toulouse.
Eastlund, B.J. and Jenkins, L.M. (2000), “Space based concepts for taming tornadoes”, IAF-00-R.3.08, 51st International Astronautical Congress, 2-6 October 2000, Rio de Janeiro.
Glaser, P.E. (1968), “Power from space, its future”, Science, 162, pp. 857-866.
Grey, J. and Deschamps, L. (1989) Central station electric power for spacecraft. IAF-ICOSP-89-7-4, Cleveland.
Grey, J. (2001), “Technical assessment of space solar power research program”, Journal of Aerospace Engineering, 14(2), pp. 52-58, 2001.
Greenberg, J.S. (2000), “Solar Power: the economic realities”, Aerospace America, May 2000, pp. 42-46.
Hashimoto, K., et al. (2001), “Advanced materials for global carbon dioxide recyling”, Materials Science and Engineering, A304-306, pp. 88-96.
Kaya, N. et al.(2001), “Wired Rectenna for SPS”, IAF-01-R.2.04, 52nd International Astronautical Congress, 1-5 Octobre 2001, Toulouse.
Kessler, T.L. (2001), “An Overview Of A Solar Thermal Propulsion And Power System Demonstration Applicable To Heds”, AIAA-2001-4777.
Kobayashi, T. et al. (2001), “The case study results of the application of the Space Solar Power System to Japanese power utilities”, IAF-01-R.3.04, 52nd International Astronautical Congress, 1-5 Octobre 2001, Toulouse.
Kruzhilin, Y. (1992), “Laser Prospects for a Solar Power Satellite and Restoration of Ozone Layer”, SPS RIO 92.
Mankins, J.C. and Howell, J. (2000), “Overview of the Space Exploratory Research and Technology Program”, AIAA-2000-3060.
Mankins, J.C. (2001), “Space Solar Power: a major new energy option?”, Journal of Aerospace Engineering, 14(2) pp. 38-45.
Martin, J. et al. (2000), “In-space transportation for GEO Space Solar Power satellites”, AIAA-2000-3857, 36th Joint Proplusion Conference and Exhibit, 17-19 July 2000, Hunstville, Alabama.
Mori, M. et al. (2001), “Summary of studies on space solar power systems of the National Space Development Agency of Japan”, IAF-01-R.1.04, 52nd International Astronautical Congress, 1-5 Octobre 2001, Toulouse.
Mullins, C. et al. (2000), “Assessment of markets for on-orbit power beaming”, 1AF-00-R.3.01, 51st International Astronautical Congress, 2-6 October 2000, Rio de Janeiro.
NASA (1997) National Aeronautics and Space Administration, Space Solar Power: A Fresh Look at the Feasibility of Generating Solar Power in Space for Use on Earth, Report Number SAIC-97/1005, Contract NAS3-26565, Task Order 9, April 4, 1997.
Ninneman, R., M. Vigil and D. Founds (2001), “Projected Technology Needs for an Operational Space based Laser System”, AIAA-2001-2863.
Pignolet, G., et al. (2000), “Using WPT in orbit as a service to microgravity research” , IAF-00-R.3.02, 51st International Astronautical Congress, 2-6 October 2000, Rio de Janeiro.
Salin, P.A. (2001), “Legal implications of the co-habitation of space solar power systems and satellite communication systems”, IAA-01-IAA.7.1.04, 52nd International Astronautical Congress, 1-5 Octobre 2001, Toulouse.
Toussaint, M. (1992), « Energy Transmission in Space », L’Onde Electrique, Vol. 72, n° 6.
Way D.W. and Olds J.R. (2001), “Space transfer vehicle concept for deploying solar power satellites”, Journal of Aerospace Engineering, 14(2), pp. 65-71, 2001.
Willenberg, H., M. Henley, S. Potter and S. Kent (1999), “Space Solar Power End-To-End Architecture Study”, presented at the Space Technology and Applications International Forum / 16th Symposium on Space Nuclear Power and Propulsion, Jan. 31 - Feb. 4, 1999, Albuquerque, NM.