MSc Program
Renewable Energy in Central and Eastern Europe

Comparing Space Based and Earth Based Solar Power - an Analysis of Technological, Energetic, Environmental and Economic aspects

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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15.11.2016, Vienna

Affidavit

I, **Shokouh Moosaie**, hereby declare

1. that I am the sole author of the present Master Thesis, "Comparing Space Based and Earth Based Solar Power - an Analysis of Technological, Energetic, Environmental and Economic aspects", 89 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master Thesis as an examination paper in any form in Austria or abroad.

Vienna, 15.11.2016 ____________________________

Date Signature

Abstract

Worldwide energy demand has continuously increased due to a growing population, a change in living standards and etc.

Increased energy demand causes a considerable use of fossil sources and, as a result, global environmental change. The world today has to face many problems such as air and water pollution, greenhouse gas emission, global warming and a pending environmental crises, which must not be ignored. Furthermore, fossil sources are limited and not clean. That is why it is necessary to use alternative energy sources which are reliable, renewable, sustainable and clean.

According to the scientists, sun is the largest available potential energy source. However, the amount of sun energy we can receive and use on earth is only one part of the high potential sun energy output. For many years scientists have been researching the possibility of using the sun power for generating electric energy directly in the space, where solar energy is much greater than the solar energy we receive on earth. The objective is to transmit this energy to the earth wirelessly via laser or microwave and to convert it back to electrical energy. Moreover, many studies have been made on wireless transmission techniques. Today, solar energy is also used on the Spacecraft. It seems that the promising technology will make it possible to use the great amount of solar energy for billions of years and solve the future energy crisis on our planet while keeping the environment clean. In recent years space based solar power has become a more and more interesting topic as it seems to be a sustainable energy solution and economically valuable.

Although space based solar energy has a high potential and is environmental friendly, according to experts it is still has to face many challenges and key barriers have to be overcome in order to approach the market.

This paper aims to assess the current status and the future perspectives of the Space Based Solar Power (SBSP), in comparison to the Earth Based Solar Power (EBSP), considering the technological, energetic, environmental and economic aspects of both technologies.

The objective of this research and the comparison between both systems is to review and analyse existing information on the potentially best use of solar energy.

To my sister Azar

"Imagination is more important than knowledge. For knowledge is limited to all we now know and understand, while imagination embraces the entire world, and all there ever will be to know and understand"

Albert Einstein

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List of abbreviations and symbols

AC .... Alternating Current
ADR .... Active Debris Removal
ALPHA .... Arbitrarily Large Phased Array
BCE .... Beam Collection efficiency
BOS .... Balance of System
CAES .... Compressed Air
CIS .... Copper Indium Selenide
CO2 .... Carbon dioxide
COPUOS .... Committee on the Peaceful Uses of Outer Space
CSG .... Guiana Space Center
DC .... Direct current
DLR .... German Aerospace Center
DOE .... Department of Energy
EADS .... European Aeronautic Defense and Space
EBSP .... Earth Based Solar Power
eGRID .... Emissions & Generation Resource Integrated Database
EPBT .... Energy Pay Back Time
ERDA .... Energy Research and Development Agency
ERF .... Energy return factors
ESA .... European Space Agency
ETO .... Earth-to-Orbit (Transportation)
FLH .... Full load hour
GaAs .... Gallium arsenide
Ge .... Germanium
GEO .... Geostationary Earth Orbit
GHG .... Greenhouse gases
GTO .... Geostationary transfer orbit
HCL .... Hhydrochloric acid
H_2Se .... Hhydrogen Selenide
IAA .... International Academy of Astronautics
Ibs/MWh .... Pounds of emissions emitted per the megawatts of electricity
IAEA .... International Atomic Energy Agency
IEA .... International Energy agency
InGaP .... Indium Gallium phosphide
InP .... Indium phosphide
IPCC .... Intergovernmental Panel on Climate Chang
IRR .... Internal rate of return
ISC .... Integrated Symmetrical Concentrator
ISM .... Industrial, Scientific, and Medical (RF Bands)
ISO .... International Organization for standardization
ISY-METS .... International Space Year-Microwave Energy Transmission
ITU .... International Telecommunication Unit
JAXA .... Japan Aerospace Exploration Agency
LCA .... Life cycle assessment

LCOE .... Levelised cost of electricity
LEO .... Low Earth Orbit
LNG .... Liquefied natural gas
L-SSPS .... Laser based SSPS
MEO .... Medium Earth Orbit
METI .... Ministry of Economy Trade and Industry
MPT .... Microwave Power Transmission
MT .... Metric tons
MWP .... Microwave Power
NASA .... National Aeronautics and Space Administration
Nd:YAG .... Neodymium doped yttrium aluminum grant
NGO .... Non-government organization
NIAC .... NASA Innovative Advanced Concepts (Program)
NO2 .... Nitrogen dioxide
NPV .... Net present value
NRC .... National Research Council
OMEGA .... Orb shape membrane energy gathering array
O&M .... Operation and maintenance
OPV .... Organic Photovoltaics
OTA .... Office of Technology Assessment
OTV .... Orbit transfer vehicle
PHES .... Pumped hydro power energy storage
PMAD .... Power management and distribution
PR .... Performance ratio
PV .... Photovoltaic
PVPS .... Photovoltaic Power System Program
Rectenna .... Rectifying Antenna
RE .... Renewable Energy
RLV .... Reusable Launch Vehicle
SBSP .... Space Based Solar Power
SCTM .... Space solar power Concepts & Technology Maturation
SEG .... Space Energy group
SERT .... Exploratory Research and Technology
SE&U .... Space Exploration and Utilization
SG .... Smart grid
SPS .... Solar Power Satellite
SSP .... Space Solar Power
SSPS .... Space Solar Power Station/Space Solar Power Satellite
TSTO .... Two-stage-to-Orbit (RLV)
TW .... Terawatt
UN .... United Nations
USEF .... Unmanned Space Expriment Free Flyer
VRE .... Variable Renewable Electricity
WACC .... Weighted average cost of capital

History

No.	Date	Version	Change
1.	18.09.2016	V1.0	Initial Version
2.	12.11.2016	V2.0	Final Version

1 INTRODUCTION

1.1 Motivation

It is a matter of fact, that the world will be confronted with an energy and environmental crisis in the near future due to some of the following reasons:

- In recent times energy demand has continuously increased in our everyday lives.
- The huge energy consumption has made the world dependent on fossil fuels and nuclear. However, such sources are limited, not available worldwide and not environmentally friendly.
- The people around the world have no equal access to the energy sources and in some cases no access at all.
- In recent times climate change, global warming, air and water pollution have been significant.

Such reasons led scientists and researchers to use renewable energy sources as an alternative. Although renewables are unlimited, sustainable and nearly eco–friendly, the current renewable energies such as biogas, biomass, geothermal, hydro, ocean, solar and wind are not yet sufficient to meet the continuously increasing energy demand. Furthermore, with regard to some of them, problems such as need of farm land and water, safety risk etc., have to be faced.

Luckily, according to scientists, power from space would be a solution. Sun is the largest available clean and safe energy source. However, the amount of sun energy we can receive and use on our planet, is only a part of the high potential of sun energy. The output is affected by the day / night cycle, atmospheric and weather conditions and as a result, the access to solar radiation on earth is limited. For many years, scientists have been researching solar power generation directly in the space, where solar energy availability is considerably greater than on the earth. According to researchers, promising new technologies will make it possible to use the great amount of solar energy in space, generate electricity, use it in space and also transmit it to the earth wirelessly. In this way it would be available in any location worldwide, where it is needed. This concept is called Space Based Solar Power (SBSP) and is also referred to as Space Solar Power System (SSPS). Realizing this vision would provide the opportunity to use high potential energy sources such as the sun. It has to be taken into account that the sun is one of the most enormous energy sources we know. If SBSP is successfully realized, the energy and environmental crisis could be avoided.

The main motivation for my research on the most efficient use of solar energy is to make a contribution to solving the problem of energy and environmental crisis.

1.2 Objective of this Master Thesis

This thesis aims to review and assess the current state and future perspective of the Space Based Solar Power (SBSP) in comparison to Earth Based Solar Power (EBSP), considering the technological, energetic, environmental and economic aspects of both technologies.

The objective of this research and the comparison between both systems is to review existing information and to assess the potentially best use of solar energy.

1.3 Major Questions

My research will focus on answering the following questions:

- What is the current status of Space Based Solar Power (SBSP) and Earth Based Solar Power (EBSP)?
- What are the future perspectives of SBSP and EBSP?
- To what extent is SBSP feasible and safe and what are the key barriers to SBSP?
- What are the advantages and disadvantages of SBSP in comparison to EBSP?
- Will SBSP be able to solve the problem energy and environmental crisis on our planet?
- What are open questions with regard to the future use of SBSP?

1.4 Method of approach

In this paper, both Space Based Solar Power and Earth Based Solar Power will be briefly reviewed, analysed and assessed considering the following aspects:

- Technological aspect: state of the art technologies will be briefly described.
- Energetic aspect: the potential production of power will be analyzed.
- Environmental aspect: potential environmental impacts will be considered.
- Economic aspect: investment potentials and risk factors will be assessed.

With regard to the four mentioned appraisals, barriers are considered and will be described.

Since the state of the art SPSP uses photovoltaic technology to generate electricity, in order to make a reasonable analysis and comparison, the earth photovoltaic based solar power generation is compared to it.

After analysing both systems, the summarised comparison and conclusion will be given.

The literature and major data used for this paper are gathered from the available sources like recent published papers on the topic, technical data from countries and companies involved in the subject, MSc Program Lecturers-Scripts, other relevant reference materials and expert discussion whenever possible.

2 BACKGROUND

2.1 Solar System

Since the ancient times, astronomy has been one of the most interesting and important fields of science. An important part of this field of science is our solar system, which includes the sun and the objects that gravitationally orbit it. Aristotle, Nicolaus Copernicus, Galileo Galilei, Johannes Kepler, Ptolerny, Sir Isaac Newton are some of the famous scientist and astronomers. Many years ago astronomers had the idea that the earth is the center of the solar system. In the 16th century, Nicolaus Copernicus, which is famous as a founder of modern astronomy, introduced the idea that the sun (helios) is at the center of the solar system (heliocentric).

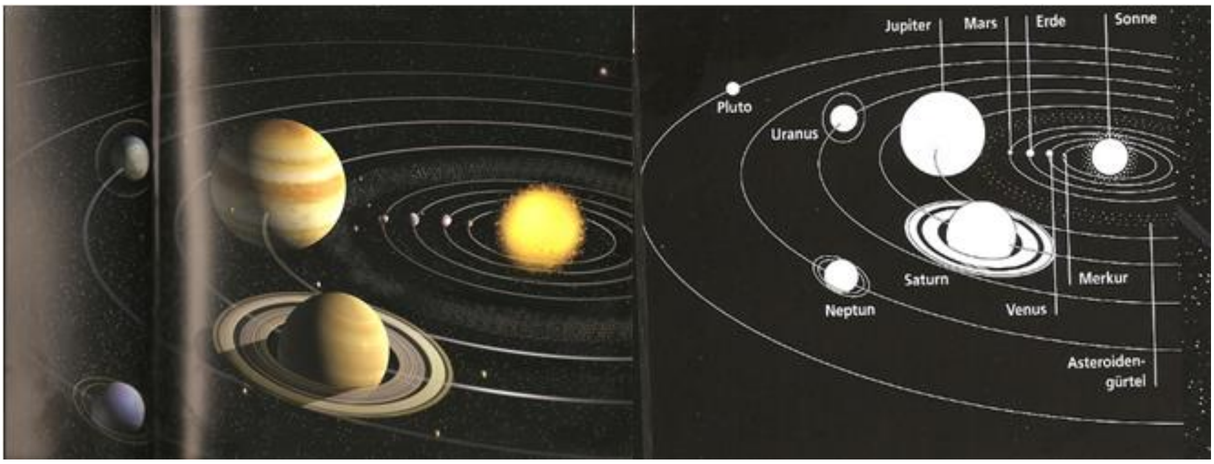

Figure 1: Solar System (Source: Book: Wissen neu erleben ASTRONOMIE: 70)[1]

Since then, development of technologies led scientists and astronomers to find a way to explain the motion of the planets. Sir Isaac Newton is one of the famous one which introduced the laws of motion.

[1] Revised

2.2 Sun Structure

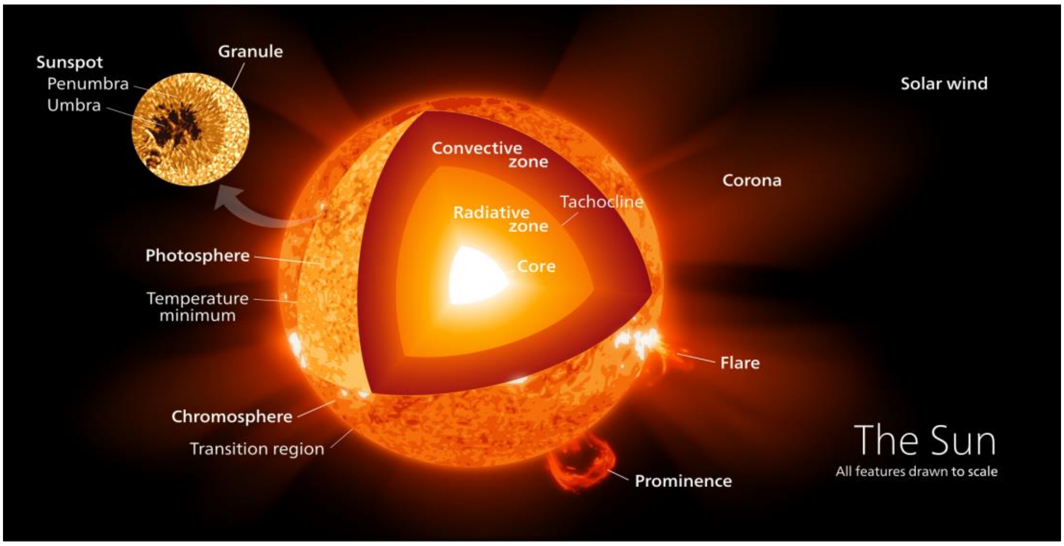

Figure 2: Sun Structure (Source: https://en.wikipedia.org/wiki/Sun)[2]

- **Core:** It is the innermost layer of the sun. The temperature is about 15.7 million degree Kelvin and density of around 150g/ cm^3

- **Radiative zone:** It is around the core and is named Radiative because of the energy transfer due to radiation. The temperature varies from 7 million to 2 million degree Kelvin and density is about 0.2g/ cm^3

- **Convective Zone:** The temperature is lower than radiative zone and is around 5700 degree Kelvin. The density is about 0.2g/ cm^3. In this layer, thermal convection will occurs when energy is carried from the Radiative zone to the photosphere.

- **Photosphere:** It is a visible surface of the sun which emits light. The temperature is around 6000 degree Kelvin.

- **Corona:** This part is plasma atmosphere around the Sun.

- **Magnetic field:** The sun has magnetic field due to the movement of convectional cells (photons and electrons) which varies across the sun surface. Magnetic field results in solar activities, e.g. solar flares.

[2] Sun Structure: https://en.wikipedia.org/wiki/Sun

The sun radiation or emitted energy can be calculated by the Einstein's Formula. It is also named sun luminosity.

$E = mc^2$ or Energy = Mass * (Speed of light)^2 (1)

Where $C = 3 \times 10^8$ m / s^2

At the proton-proton cycle, a lot of energy will liberate if one hydrogen atom converts into helium atom. The liberated energy is difference between the hydrogen nuclei and helium nuclei.

Where mass of one hydrogen nuclei = $6.693*10^{-27}$ kg and mass of one helium nuclei = $6.645*10^{-27}$ kg, then m = 0.048×10^{-27} kg

$E= (0.048 \times 10^{-27}\ kg) \times (3 \times 10^8\ m / s^2)^2 = 0.043 \times 10^{-11} J$

Where 1 Joule = 1 kgm^2 / s^2

As Seboldt (2004) mentioned, the Sun's radiation (flux) in space is 1.368 W/m², while the available Sun's radiation on the surface of the earth is 600-1000 W/m² due to the atmospheric effects. However, surface of the earth will receive an average continuous flux between 100 and 300 W/m² because of day/night cycle and year. According to Hosenuzzaman et al. (2015), the sun power on the surface of the earth is around 1.4 x 105 TW, while only 3.6 x 104 TW of it is usable.

According to Mankins (2014), energy loss occurs due to the day/night cycle (about 60%), weather - light clouds and heavy clouds (20% and 70% - 80% respectively). That means, availability of sun energy in space is greater than the availability of sun energy at the best area on earth.

Figure 3 gives an overview of Earth Atmosphere.

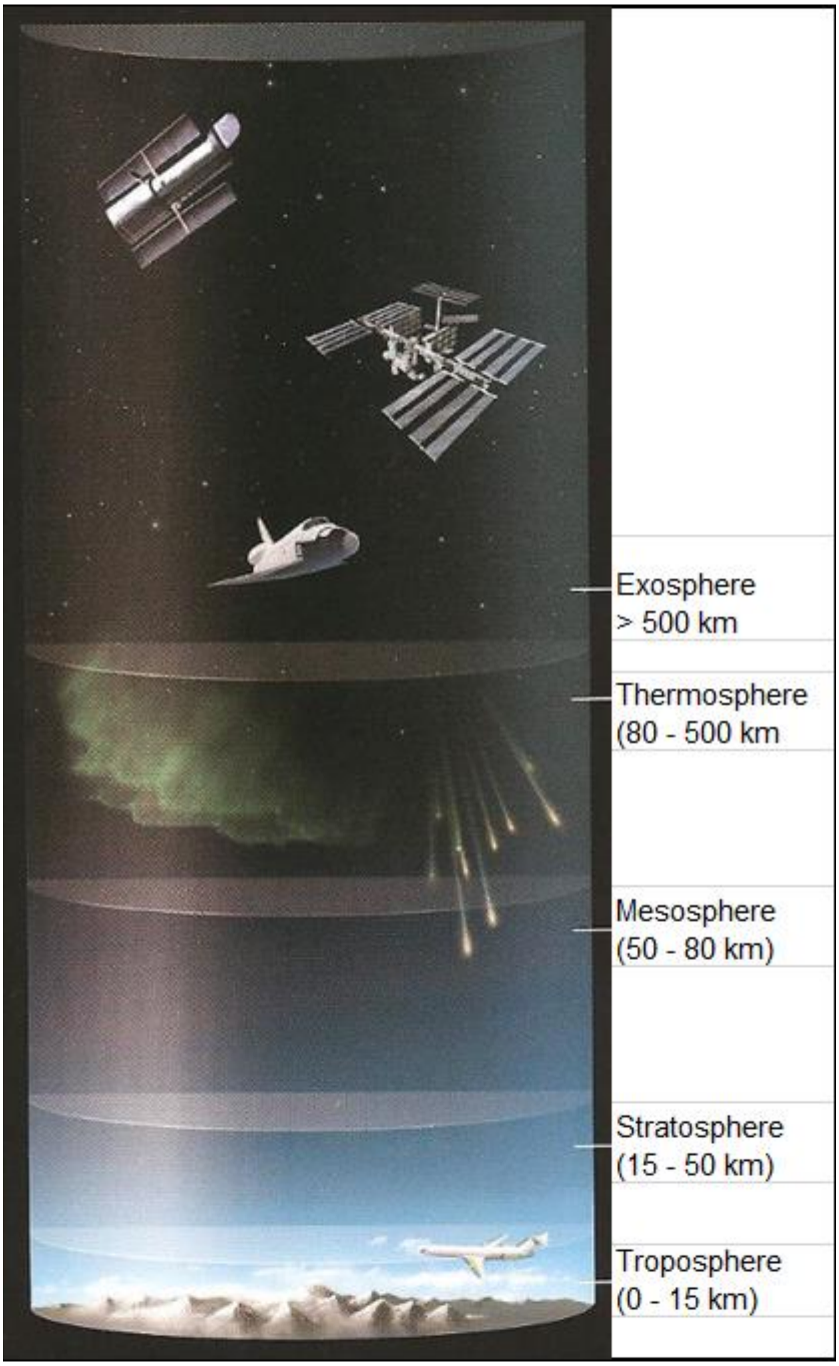

Figure 3: Earth Atmosphere (Source: Book: Wissen neu erleben ASTRONOMIE: 86)[3]

[3] Revised (Text translated from German to English)

3 Analysis of Space Based Solar Power (SBSP)

3.1 Method of approach

In order to give a clear overview of the current status and future perspective of the Space Based Solar Power (SBSP), the available data are investigated considering historical background of SSPS development, technological, energetic, environmental, economic aspects and related barriers. In this paper the terms of of SSPS (Space Solar Power System), SBSP (Space Based Solar Power), SSP (Space Solar Power) and SPS (Solar Power Satellite) are used. According to Meng et al. (2013), SSPS is also known as Space Based Solar Power. Mankinds (2014) uses term of SSP (Space Solar Power) as well as SPS (Solar Power Satellite).

Historical background: The history of SSPS development during the last decades is described. Some examples of SPS concepts introduced by the US, Japan and Europe are presented.

Current status:

- **Technological appraisal:** The recent SSPS concept design, both in progress or planned, is described as well as state of the art technologies which are currently used in SSPS design.
- **Energetic appraisal:** The estimated capacity and system efficiency of the most developed SSPS concepts is discussed.
- **Environmental appraisal**: SSPS environmental impacts are described. LCA (Life Cycle Assessment) is discussed based on the relevant researched literatures.
- **Economic appraisal**: Major factors for the business case of SBSP are described. Moreover, the estimated total cost for one of the promised SSPS system is given.
- **Relevant barriers**: With regard to the four mentioned appraisals, barriers are considered and presented.

Future perspective:

The status of most improved technical SSPS concept which is still at an experimental stage and might be realized is briefly described. Moreover, Japan’s plan and relevant stepwise approach to build a commercial SSPS till 2030 is presented.

3.2 Historical background of SBSP development

The first idea of space solar power station (SSPS) was introduced by Dr. Peter Glaser in the United States around 1968. The basic idea was collecting solar energy in the space by use of solar cells in the earth orbit, generate electricity and beam it down to a receiver at the earth via wireless power transmission (see Figure 4). Solar power satellite was also invented by him. Space based solar power is a method to capture and collect the high potential solar energy in space and to convert it to electricity. Then it can be used in space or delivered to earth via wireless power transmission (WPT) to provide base load power. Space solar power satellite (SSPS) will be located in earth orbits for the functionality (Mankins 2009; Jaffe et al., 2014; Yang et al., 2016).

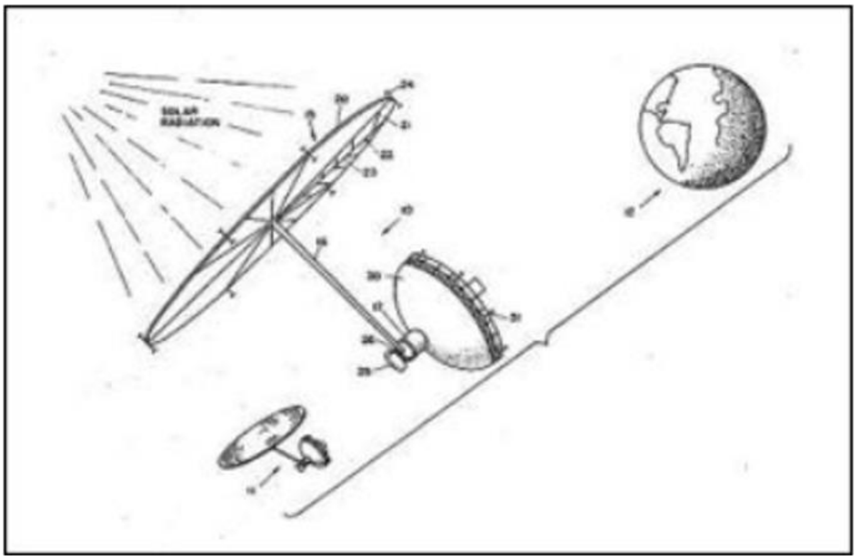

Figure 4**:** SPS concept-1973 from Peter Glaser **(**Mankins, 2014: 44)

History of WPT comes back to Nicol Tesla about 100 years ago. It was a key component of technology to deliver power from space to the ground (Mankins, 2014).

Since introducing SSPS concept by Peter Glaser, numerous efforts have been made by the researchers, scientists, government agencies and aerospace companies as well as universities to make the SSPS vision technically and commercially realize. For example, different SSPS concepts have been introduced by NASA/DOE of US, JAXA of Japan and ESA of Europa based on the Dr. Peter Glaser idea (Yang et al., 2016).

The history of research about space based solar power comes back to the oil crisis during 1970s which caused the high gasoline demand in the US and led to research on the most efficient use of solar energy. Many research and studies were made by US scientists of National Aeronautics Space Administration (NASA) and the Department of Energy (DOE) on possibility of putting satellites with large solar arrays in the geosynchronous orbit and transmit the energy to the earth via microwave antenna (Mankins, 2009).

In the United States, the major studies about SSPS have been done in the 1970s by the Energy Research and Development Agency (ERDA) in cooperation with the National Aeronautics and Space Administration (NASA) (Mankins, 2014). Furthermore, National Aeronautics Space Administration (NASA) and Department of Energy (DOE) together did also serious studies about SSPS during 1976 and 1980**.** These studies led to creation the foundational structure of SSPS. It was a large scale system in space including of around 60 SPSS. Each of them could deliver 5 GW base load power to U.S electrical gird. Furthermore, the locations of rectifying antenna on the earth and lighting protection for it were investigated. Study was also done on atmospheric effects related to rectenna. The results of these major studies and research showed that SSPS is technically feasible. Re-assessing the concept, in about ten years, was recommended by U.S. National Research Council (NRC). Also technology development and maturation was suggested. (Bergsrud & Straub, 2014).

However, in early 1980s, all US government activities related to SPS were terminated due to some negative assessment of technology and development plan – which had been done by the Office of Technology Assessment (OTA) of the US congress and the National Research Council (NRC), in addition to US administration change in 1980. In the 1980s, examine of SPS concept continued by non-government organisation (NGOs) such as SUNSAT Energy Council as well as by international researchers. Significant technology progress was done during 1980s and 1990s. In 1990s, SPS was reviewed again by the US government through NASA's "Fresh Look Study" which resulted in tecnology development road map (Mankins, 2009).

During the 1980s and 1990s, SSPS concept became a topic of international interest in Japan, Europa and Canada. Especially, in Japan, the first successfully Microwave Wireless Power (MWP) transmission conducted by Japanese researchers from Koyoto University in 1983. It is named Microwave Ionosphere Nonlinear Interaction Experiment (MINIX) (Nagatomo et al., 1986; Bergsrud & Straub, 2014**)**. Also, in 1993, a project was conducted and successfully completed by another Japanese researchers. The project was ***"****International*

Space Year-Microwave Energy Transmission in Space (ISY-METS) S-520-16 sounding rocket experiment" (Bergsrud & Straub, 2014: 194).

In 1990s, NASA studied again on the large scale SSPS (through the "Fresh Look study") (Mankins 2009; Bergsrud & Straub, 2014). Different SSPs concept and architecture were examined through Fresh Look study aiming to deliver power to the Earth in GW class. Fresh Look study aimed to reduction the system scale, mass, major part such as power management and distribution (PMAD) and using of modular system strategy (Mankins, 2009). The study led to more technical viability for SSPS than before. High energy demand and climate change led US National Research Council (NRC) to review the "Fresh look study" in 2000, and SPS concept became more technically feasible than before due to the progress of technology, but it was still not economically feasible (Mankins, 2009). In 2000, NASA (led by NASA Marshall Space Flight Center (MSFC)) conducted the SSP Exploratory Research and Technology (SERT) program (Feingold & Carrington, 2003; Mankins, 2009; Bergsrud & Straub, 2014). This study program was the third part of program studies by NASA started in the 1995 "Fresh Look" and study of SSP concept definition in 1998. All these three studies focused mainly on SSP concept, technology and architecture to find a viable power system for the earth. The studies led to use of microwave for SSP in a simple and low cost system which was easy to assemble. The system composed of a Sun Tower and at the bottom of it a phased-array large microwave transmitter towards the earth. Figure 5 shows the original version of Sun Tower. However, some technical problems caused an inefficient operation in Geosynchronous Earth Orbit (GEO) which was even better location for the system than Medium Earth Orbit (MEO) for delivering power to the earth, e.g. running heavy electrical cables in kilometres (Feingold & Carrington, 2003). The SERT program focused on different aims such as system technical viability, research and development activities for testing the SSP validity (Mankins, 2009; Bergsrud & Straub, 2014). Finally, in 1998, the SERT program had a major result in a SPS concept which is called ISC (Integrated Symmetrical Concentrator) in which the system mass reduction was promising but researchers were concerned about thermal management. (Mankins, 2009). The study was continued in 2001-2002 by a program named Space solar power Concepts & Technology Maturation (SCTM). The goal of the program was concept improvement and technology advancing for future in the criteria of: (Seboldt, 2004)

- *"Wireless power transmission (WPT)*
- *Intelligent robotics*
- *Power management and distribution and control (PMAD)*
- *Potential technology flight experiments"* (Seboldt, 2004: 395)

Another SPS concept studied and conducted by German Aerospace Center (DLR) in 1998/99 in cooperation with ESA. The study made on the system concept as well as on Architectures and Technologies for Space Exploration and Utilization (SE&U). This concept called "European Sail Tower SPS" (See Figure 6). Although the system design was based on the Sun Tower from NASA (inspired), they also used their own under developing Sail Tower technology (Seboldt, 2004).

Figure 5: Sun Tower - Original Version (Feingold & Carrington, 2003: 545)

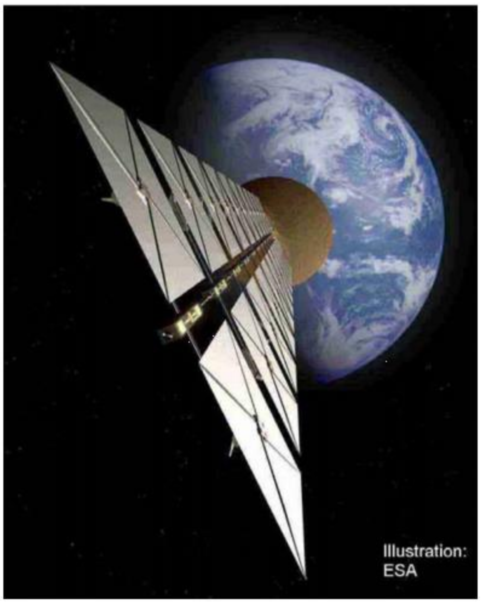

Figure 6: SPS concept in GEO - European Sail Tower (Seboldt, 2004)

Also, JAPAN Aerospace Exploration Agency (JAXA) has studied on Solar Power System since FY1998 for commercial type of microwave based SSPS (M-SSPS) and Laser based

SSPS (L-SSPS) (Mori et al., 2006). The SPS 2000 project in Japan aimed to put the SPS in the LEO orbit in MW-class (Seboldt, 2004). In 2001, tethered solar power satellite (Tethered – SSPS) introduced by Japanese government METI (Ministry of Economy, Trade and Industry) and Institute of Unmanned Space Expriment Free Flyer (USEF) (Sasaki et al., 2007; Yang et al., 2016).

For many years, several efforts have been made aiming to realize SSPS vision. For example, one of the important and interesting project was MWP transmission in Hawaii in 2008. The project performed by Mankins from Managed Energy Technologies in cooperation with other researchers of Texas A&M University and University of Kobe. The transmission power was experimented from Maui to Hawaii's for over of 148 km distance while the amount of less than 0.00001 W of transmitted power was reached by the receiver. It was a considerable power loss due to the small size of both transmitting and receiving arrays (Bergsrud & Straub, 2014).

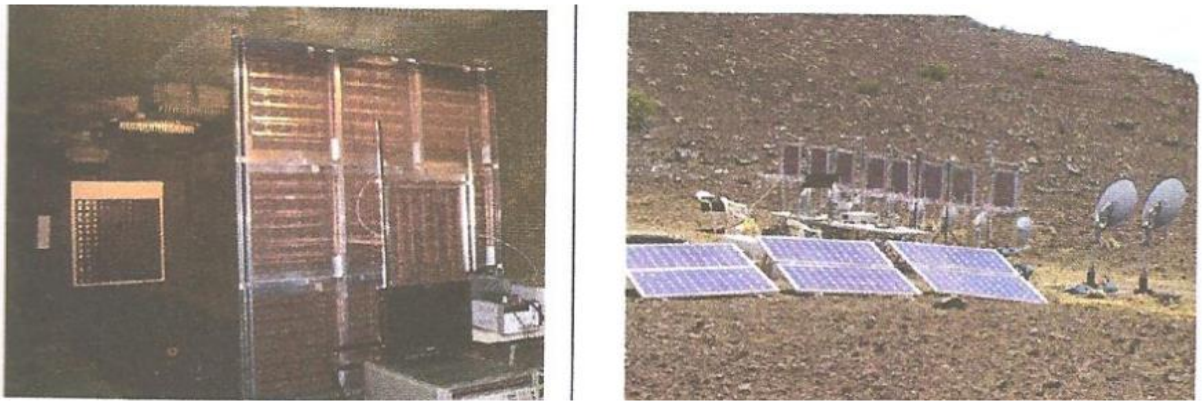

Figure 7: SSP WPT demonstration Hawaii - May 2008 (Mankins, 2014: 79)

Table 1: Typical SPS concept (Sasaki et al., 2007: 154)

Concept of typical SPS

	Reference system [1]	NEDO grand design [2]	SPS2000 [3]	Sun tower [4]	Sail tower [5]	Integrated symmetrical concentrator [6]	NASDA 2001 model [7]
Organization	NASA/DOE	NEDO	ISAS	NASA	ESA	NASA	NASDA (JAXA)
Year	1979	1992	1993	1995	1999	2001	2001
Power	5 GW	1 GW	10 MW	250 MW	450 MW	1.2 GW	1 GW
Orbit	GEO	GEO	LEO	MEO	GEO	GEO	GEO
Configuration	Single rectangular solar array panel, circular disk antenna	Two rectangular solar array panels, circular disk antenna	Triangular prism, solar array on the upper two panels, transmitter on the lower panel	Tree-like tower, modular structure for power generation, circular disk antenna	Flower-like tower, sun-tracking sail modules for power generation, circular disk antenna	Two clamshell condenser mirrors, separated power generator and transmitter	Two primary mirror, two secondary mirrors, sandwich panel
Bus power	Yes	Yes	Yes	Yes	Yes	Yes	No
Rotary joint	Yes	Yes	No	Yes	Yes	No	No
Rotating light-condenser mirror	No	No	No	Fixed condenser	No	Yes	Yes

GEO: geo-synchronous orbit; MEO: medium earth orbit; LEO: low earth orbit.

Table 2: Some typical SSPS concepts (Meng et al., 2013: 293)

Typical SSPS concepts.

Model		Organization	Configuration	Output power	Tracking method
Non-concentrator	Tethered-SPS	USEF	Simple 'Sandwich' panel	1.2 GW	No track control
	Abacus Reflector	NASA	Solar panel with sun-oriented array transmitter	1.2 GW	Use rotatable RF reflector to track the earth
	SolarDisc	NASA	Rotated PV disc and RF generator	1–10 GW	Multiple ground sites to share time-phased power transmission
Concentrator	Sun Tower	NASA	Tree-like tower, highly modular structure, fresnel thin film concentrator	250 MW	Need multiple ground sites and storage system
	ISC	NASA	Two symmetrical off-axis dish concentrators	1.2 GW	Flexible joint and mast ensure the orbital tracking
	NASDA 2001	NASDA (JAXA)	Cassegrain-type concentrator, Sandwich panel	1 GW	Use rotatable two stage mirrors to track
	Alpha SPS	NASA	Bodymounted, axisymmetric structure, large number of heliostats	0.01–1 GW	Each heliostat smartly keeps tracking the sun

Table 3: Some typical SSPS concepts (Yang et al., 2016: 52)

Typical SSPS concepts.

	Reference model [11]	Sun tower [12]	Solar disc [4]	ISC [4]	Sun Sail [4]	Tethered- SSPS [8]	ALPHA [13]
Year	1979	1995	1997	1998	1999	2001	2012
Organization	NASA/ DOE	NASA	NASA	NASA	ESA	METI/ USEF	Artemis
Orbit	GEO	LEO	GEO	GEO	GEO	GEO	GEO
Power (GW)	5	0.1–0.4	1–10	1.2	0.275	0.75	2
Frequency (GHz)	2.45	5.8	5.8	2.45	2.45	5.8	2.45
Mass (MT)	30,000–50,000	2000–7000	8000–70,000	35,000	3750	3800	25,260*
Focus	Non	Point	Non	Point	Non	Non	Distributed
Modularity	Monolithic	Modular	Monolithic	Modular	Modular	Modular	Modular

* The data is from the ALPHA DRM 5/Case_4B, a mature full-scale SSPS with 2 GW power for commercial markets, which might to be realized at least 30 years.

3.2.1 Typical SSPS concepts

Typical SSPS concepts based on the different method of focusing (non-focusing, point-focusing and distributed focusing (Yang et al., 2016) are briefly described below:

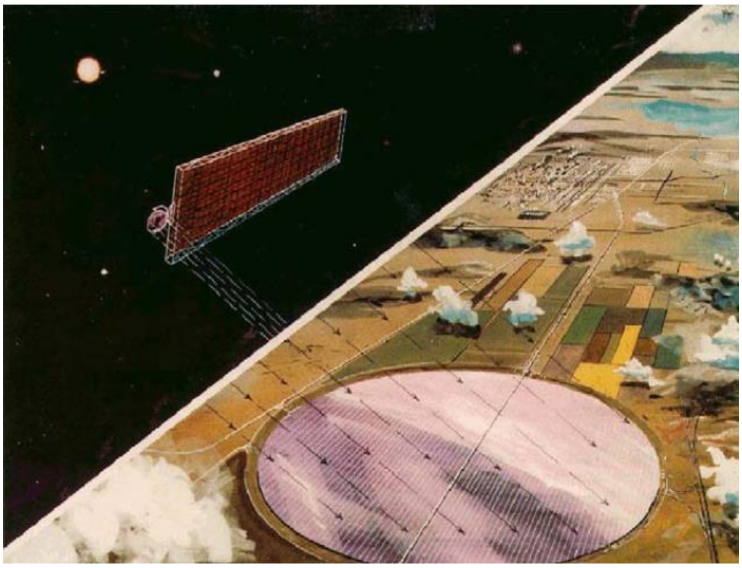

Figure 8: 1979 SPS reference system **(**Mankins, 2009: 147)

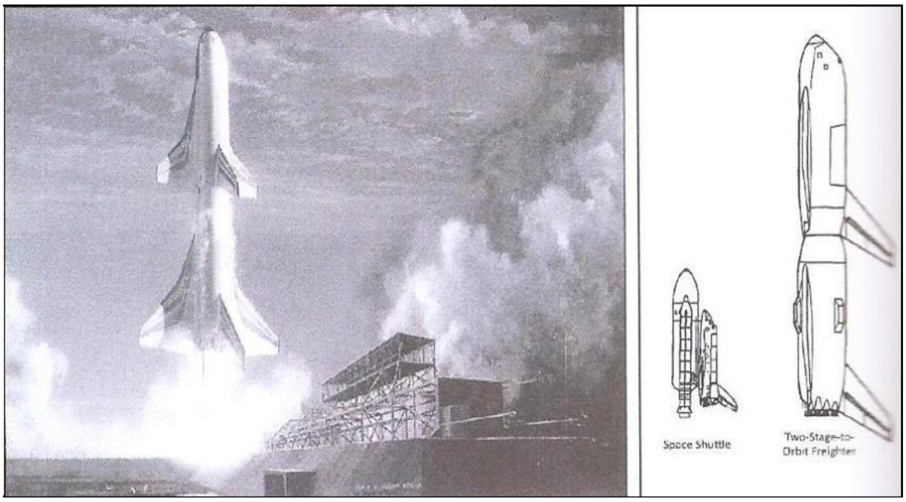

Figure 9: 1979 SPS reference system-TSTO ETO Transportation (Mankins, 2014: 230)

Figure 9 shows Earth-to-Orbit Transportation of reference model via TSTO (Two-stage-to-Orbit via Reusable Launch Vehicle (RLV)).

- **Non-focusing :**

The reference model, as shown in Figure 8, is a typical non-focusing concept, introduced by NASA/DOE in 1979 (Sasaki et al., 2007; Yang et al., 2016). The reference model comprises the major parts as follows:

- A single Large solar array panel around of 50,000 m^2
- A microwave transmitting antenna
- Rotary joint connecting the panel and the antenna
- Receiver on the Earth

The reference model was technically complex due to difficulties of rotary joint mechanism and power collection. With respect to rotary joint mechanism, a power transmission mechanism is essential in GW level to prevent serious power loss. However, in this regard, there is no practical technology. With regard to power collection, a super-conduction system or huge amount of conductor is needed for power transmission line between array panel and microwave transmitter, otherwise a serious Joule loss will occur (Sasaki et al., 2007). Furthermore, the system needed high initial investment (Yang et al., 2016).

Another typical Non-focusing concept is tethered solar power satellite (Tethered – SSPS) introduced by Japanese government METI (Ministry of Economy, Trade and Industry) and Institute of Unmanned Space Experiment Free Flyer (USEF) in 2001 and 2002 (Sasaki et al., 2007; Yang et al., 2016). Figure 10 shows the model concept (Sasaki et al., 2007). The model is composed of the major parts as follows:

- A large power generation / transmission panel consist of 400 equivalent subpanels. The panel suspended by multi wires deployed from a bus system.
- Power generation / transmission modules. Each module consists of:
  - Thin film solar cells on both sides of panel (upper and lower side)
  - Power processor
  - microwave circuit
  - Controller
- A microwave transmitting antenna is located on the lower panel

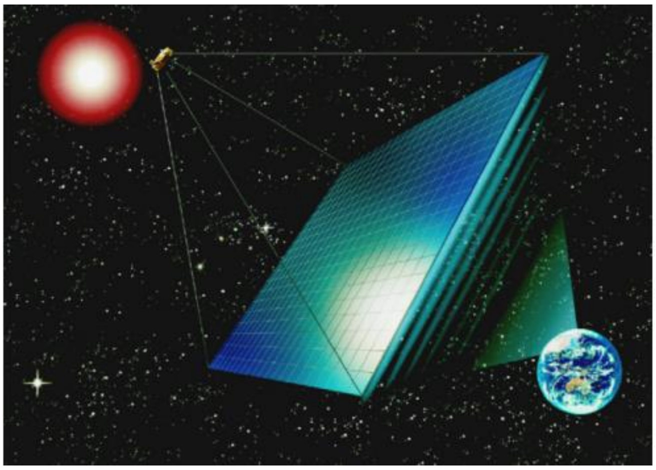

Figure 10: Tethered-SPS- Artist conception (Sasaki et al., 2007: 154)

Summary of Tethered-SPS are shown in Table 4.

Table 4: Tetherred-SPS (Sasaki et al., 2007: 156)

Summary of Tetherred-SPS

Configuration	Power generation/transmission panel suspended by 441 wires
Panel size	2.0 km × 1.9 km × 0.1 m
Tether wire length	10 km approx.
Total weight	20,000 MT
Panel	19,000 MT
Bus	1000 MT
Subpanel	Power generation/transmission panel suspended by four wires
Size	100 m × 95 m × 0.1 m
Total number/panel	400
Structural unit panel	
Size	10 m × 1 m × 0.1 m
Total number/subpanel	950
Module	Power generation/transmission capability
Power generation	490 W maximum
Power transmission	420 W maximum
Size	1 m × 1 m × 0.1 m
Total number/subpanel	9500
Microwave	
Frequency	5.8 GHz
Output power	1.2 GW maximum, 0.75 GW on average

The system concept has advantages of reducing complexity and mass and disadvantages such as low efficiency and fluctuation on energy collection (Yang et al., 2016). A demonstration was experimented by use of scale model of the subpanel. Also, on the ground a demonstration experiment has been researched, by use of a balloon, as a pre-experimental in orbit. Demonstration has been done for a panel of 4m x 4m and transmitting power of 17.5kW. It is possible to obtain around 7kW power on the earth, if a rectenna of 30 m diameter is used (Sasaki et al., 2007).

- **Point-focusing :**

Point focusing concept introduced by NASA in 1998. The two introduced models are described below:

- Integrating Symmetrical Concentrator (ISC)
- Symmetrical Two stages flat reflected Concentrator (STFC)

Figure 11 shows the ISC concept. *"ISC utilizes large, symmetrically placed off-axis parabolic reflectors whist receiving surface being placed on the focal plane"* (Yang et al., 2016: 51).
A system modeling and analysis determined that, till present (2003) ISC is the most- cost effective and lightest concept, compared to previous SSP concept. However, it requires a thermal management technology (Feingold & Carrington, 2003).

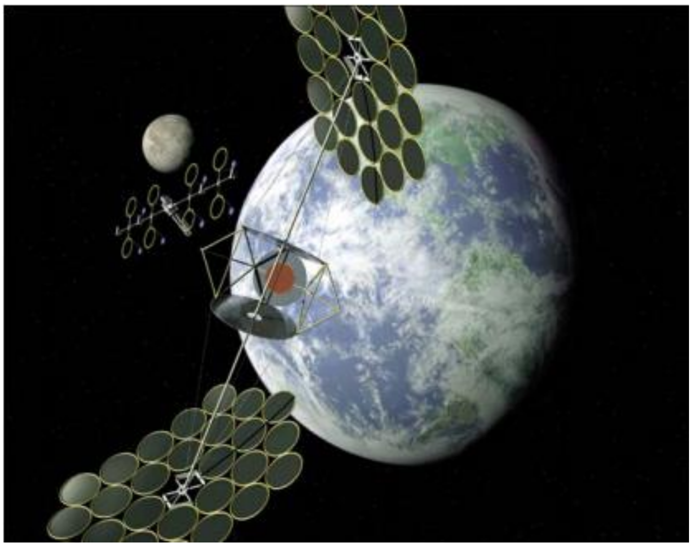

Figure 11: Integrated Symmetrical Concentrator (ISC)-(c. 2000) (Mankins, 2009: 147)

The improved ISC concept named symmetrical two stages flat reflected concentrator (STFC) in which the PV cell array, microwave devices and transmitters are integrated into sandwich structure. System is also equipped with the secondary reflectors. The parameters for main reflectors and secondary reflectors made it possible to reach a high degree of distribution uniformity and an appropriate condensation ratio (Yang, et al. 2016; Meng et al., 2013).

However, high power rotating mechanism and a complex control system was essential for both ISC and STFC (Yang et al., 2016; Mankins, 2014).

- **Distributed focusing:**

Typical distributed focusing concept proposed in 2012 by John C. Mankins from Artemis Innovation Management Solution LLC, USA. The model named ALPHA (Arbitrarily large Phased Array). ALPHA is a biomimetic and hyper modular design operating in GEO (geostationary Earth orbit). The model consists of the following major parts:

- Large sandwich structure:
    - Solar array
    - A transmission antenna
- Solar energy collecting system:
    - Large number of thin-film mirrors
- Truss structure to connect the sandwich structure and solar collecting system

The sandwich structure is a key element of SPS-ALPHA. In the system, the solar array locates at the top side. Transmission antenna is located at the bottom side towards earth. Solar energy collecting system includes thousands of movable light weight thin-film mirrors. The mirrors are individually pointed "heliostats" and are used to redirect sunlight to the high efficiency photovoltaic array. The array is fixed on the other side of the device. The electricity which is generated by PV array will be converted through a radio frequency (RF) aperture to microwave and will be delivered to the Earth (Mankins, 2014; Jaffe et al., 2014; Yang et al., 2016). Design concept and basic structure of SPS-ALPHA are shown in Figures 12, 13, 14, 15, 16 and 17.

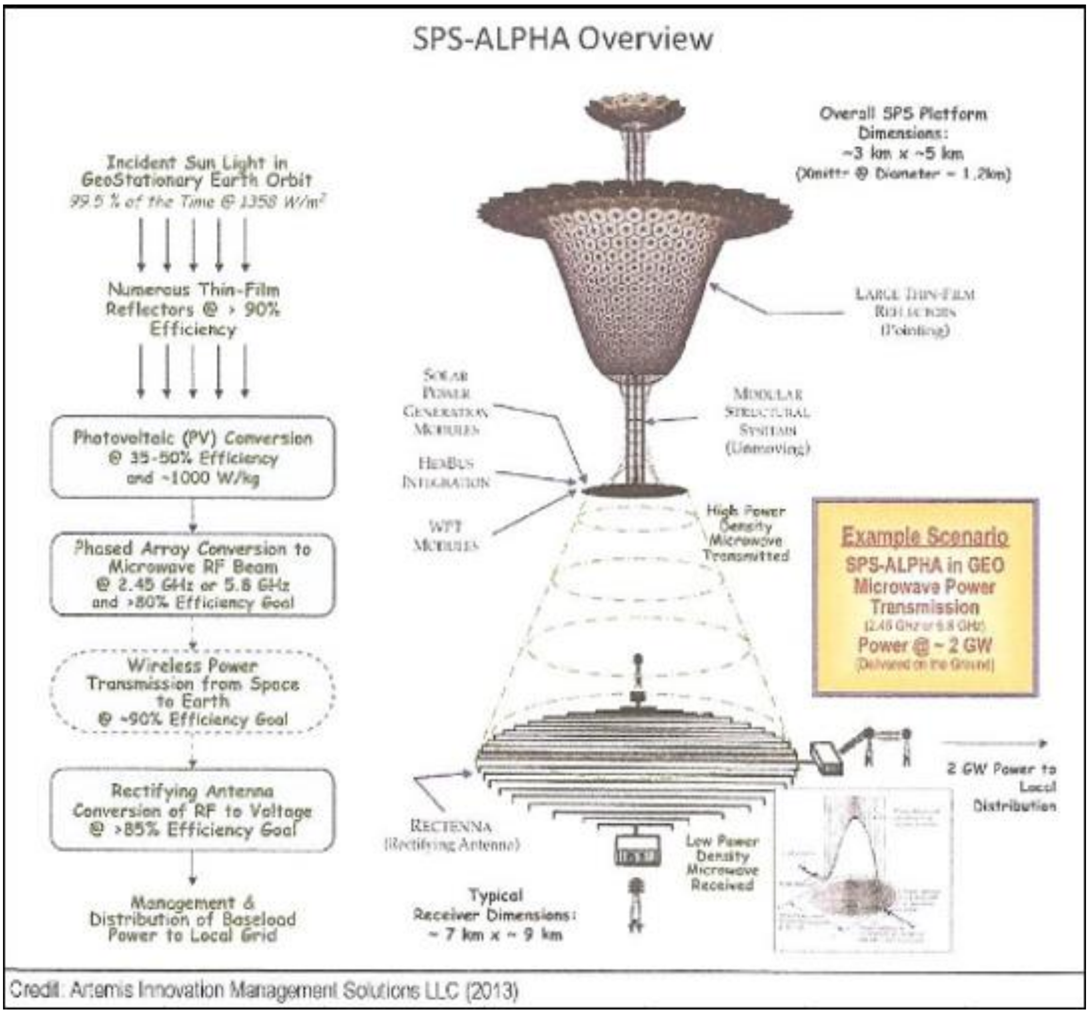

Figure 12: SPS – overall concept (Mankins, 2014: 8)

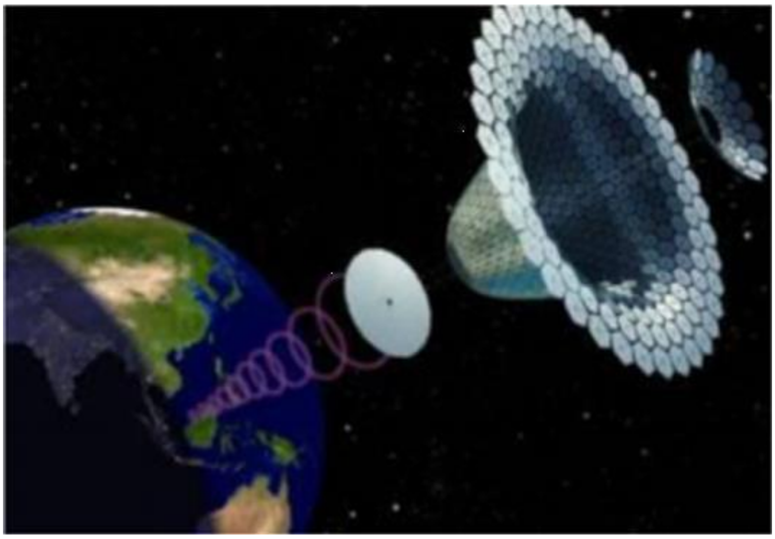

Figure 13: ALPHA concept - Basic structure (Yang et al., 2016: 52)

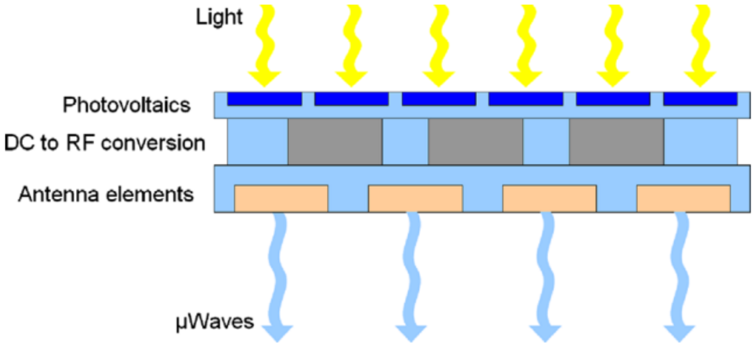

Figure 14: Sandwich module - Functional layers (Jaffe et al., 2014: 663)

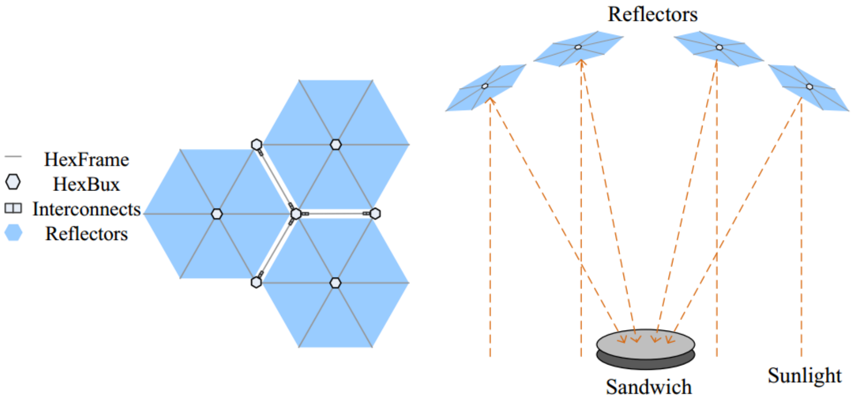

Figure 15: Structure and reflectors adjustment (Yang et al., 2016: 52)

The latest version of ALPHA introduced in 2013, in which the main reflector works based on the sigmoid curve. The secondary reflector is hyperboloid structured. Secondary reflector made it possible to increase the area of receiving energy effectively as well as efficiency of sunlight collecting. Sunlight is partly reflected by the main reflectors and the other parts are firstly reflected by the main reflector and then by the secondary mirrors (Mankins, 2014; Yang et al., 2016).

ALPHA has many advantages such as system efficiency increasing and cost reduction. However, designers were concerned about some disadvantages, e.g. thermal control (Pandey et al., 2016). ALPHA-SSPS was expected to be one of the first practical and advanced SSPS concept. However, it faced with some technical problems in design stage. System design concept was complex. For example a complicated control system was needed to adjust the reflector modules (movable mirrors). Also, high demand of thermal control was needed due to use of long electric cables between PV array and transmission antenna. Such key points have led to improve the ALPHA model and to propose a novel concept. *"The novel concept has some technical advances over some previous concepts, such as no need to integral adjustment on main reflector, low demand on thermal control,* *wired power transfer from PV array to transmitting antenna in short distance and low-mass connection structure between main reflector and transmitting antenna"* (Yang et al., 2016: 53). Then, the improved model introduced and called OMEGA (Orb shape membrane energy gathering array) (Yang et al., 2016).

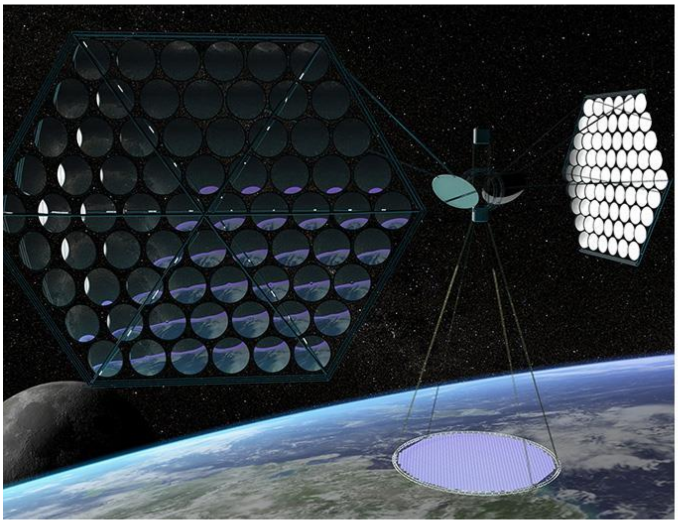

Figure 16: Architecture of Sandwich Space Solar Power (Source: Mafic studios, Inc.)[4]

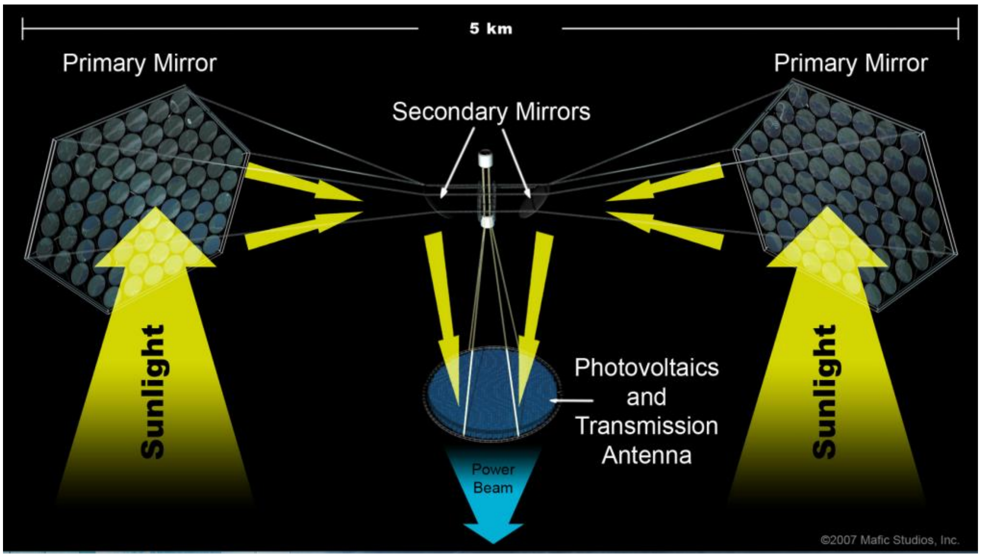

Figure 17: Modular Symmetrical Concentrator architecture (Jaffe et al., 2014: 663)

Nowadays, Space Solar Power becomes interesting as it is known as a secure, safe and clean energy. Moreover, if it realize, it will be able to supply base load power into earth's grid unaffected by day/night cycle and weather conditions. Furthermore, produced power can be

4 "Sandwich Space Solar Power", 2007. A still from an animation on SSP. Client: NSS, NSSO, http://www.maficstudios.com/gallery.html

transmitted to the earth wirelessly. Thus, it can be available in any location, where it is needed (Mankins, 2014). As already mentioned, since introducing space power station (SPS) by Dr. Peter Glaser, numerous efforts have been made to realize SSPS. For example, different SSPS concepts have been introduced by NASA/DOE of US, JAXA of Japan and ESA of Europa based on the Dr. Peter Glaser idea (Yang et al., 2016).

3.3 Current status

As Mankins (2014) discussed, although the SSP concept was invented by U.S. many years ago, currently the most activities and continuing progress are in Japan and China. These two countries have a strong interest in strategic planning for their future energy demand.

- **Development in United States**

As already mentioned, the latest most improved SSPS design called Orb shape membrane energy gathering array (OMEGA). The OMEGA is projected to supply of 2 GW power into terrestrial markets and might be realized around 2050.
However, OMEGA is still at an experimental stage from technological and economic aspects. In comparison to previous concept, OMEGA design is the most technically advanced and has some advantages as follows (Yang et al., 2016):

- No need of complex control system because an integral adjustment is not needed for main reflector.
- Reducing of heat dissipation because the solar cells array and transmitting are designed in separate parts and not in sandwich structure
- Low thermal control demand
- Low mass connection structure between main reflector and transmitting antenna because they are connected by long span cable.
- Stability in energy supplying because there is low fluctuation of solar collection with local time

SSPS-OMEGA design concept is reviewed and briefly summarized as follows: (Yang et al., 2016)

3.3.1 Technological appraisal

- **Design concept**

The OMEGA model is a modular spherical system is comprised of the following major parts:

- Reflector modules
- Photovoltaic cell array
- Power management and distribution (PMAD)
- Microwave transmitting antenna

Figure 18 and Figure 19 shows the SSPS-OMEGA concept.

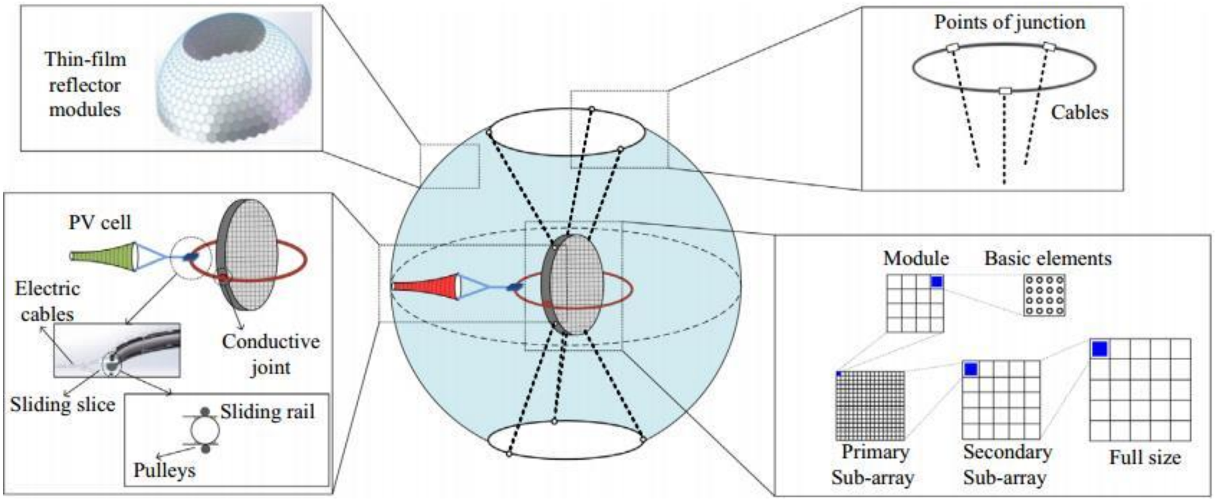

Figure 18: SSPS-OMEGA concept - Summary diagram (Yang et al., 2016: 53)

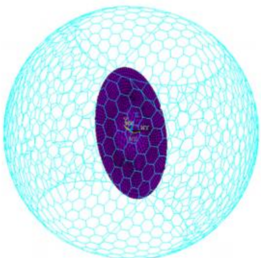

Figure 19: Connection between reflector and antenna (Yang et al., 2016: 57)

- **Technical description**

OMEGA model is a modular spherical structure system in which the main reflector collect the sunlight. Sunlight will convert to electricity by series of photovoltaic cell arrays. Produced electricity will deliver into the microwave devices through electric cables and conductive joins.

- **SSPS Performance in different Orbits**

Performance of SSPS concept is evaluated in different orbits such as low earth orbit (LEO), geostationary earth orbit (GEO), sun synchronous orbit (SSO), etc. The evaluation shows that the SSPS has a better performance in the low earth orbit (LEO) than in geostationary earth orbit (GEO). However, multiple systems are needed to provide continuous power. SSPS is expected to supply the earth's grid with baseload power. Moreover, evaluation shows that SSPS has a simple control in GEO, Therefore GEO has been chosen for OMEGA functionality. GEO complied with the most SSPS concept.

- **Reflector modules**

The reflector modules are spherical structured which responsible to reflect the collected sunlight on to the photovoltaic cell array.
"Semi-transparent and semi-reflecting thin film is promising for the realization of the spherical reflector. *Sunlight could pass through one side of the thin film whilst being reflected by the other side"* (Yang et al., 2016: 54). A large number of Reflected modules are mounted on a support structure. They rotate individually in the orbit.
In case of using control mechanism, more detail analysing needs to be done for optical path, efficiency of energy collection and main reflector mass and radius.

- **Photovoltaic cell array**

In order to convert the sunlight to electricity, series of PV cell array are considered in OMEGA design. The photovoltaic cell array is designed in hyperboloid structure. Such structure makes it possible to uniform energy distribution and increase the concentration ration of PV cell array.

- **Cell technology**

High efficiency Gallium Arsenide (GaAS) solar cell array are projected to use in the OMEGA project. According to researchers, GaAs (Gallium Arsenide) material is suitable for SSPS. GaAs is highly efficient and has high heat resistance which are the major key points in space application (Pandey et al., 2016; Yang et al., 2016). Moreover, GaAs has lower weight than the other solar cell types such as poly and monocrystalline silicon (Tyagi et al., 2013).
Recently, multi-junction solar cells have been considered for SSPS as an alternative for Si-solar cell due to ability of high energy conversion efficiency however, compared to Si-solar cell has more density, thickness and higher cost. Multi-junction solar cell has advantages to provide high amount of power when compact size of solar array is required. Many Studies have been made on different types of solar cell with regard to the cell performance economic, weight and area aspects. Recently, developed solar cell for space application have been optimised with respect to the parameters such as energy conversion efficiency, radiation resistance and cost. Efficiency of 17% has been reported for rad-hard Si-solar cell under the zero air mass while efficiency of 23% and 26% have been reported for dual-junction, triple-junction and InGaP/GaAs/Ge types under the same test condition (Pandey et al., 2016).
According to some manufacturers, Currently, GaAs is the highest performance available material which reaches boasting conversion efficiencies more than 40%, e.g. according to "Nano Flex POWER CORPORATION" manufacture[5] (see Figure 20).

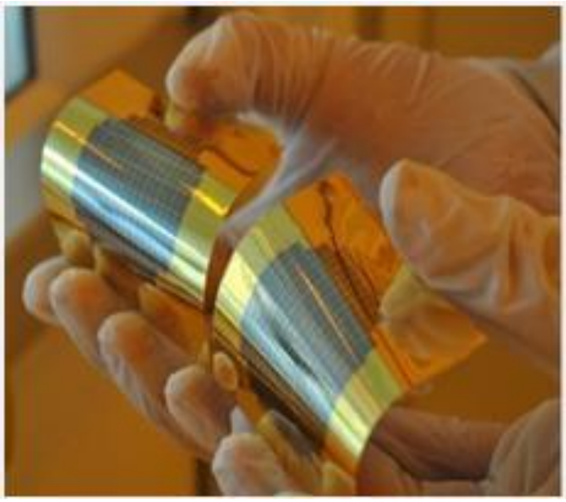

Figure 20: Gallium arsenide Solar Cells (Nano Flex POWER CORPORATION)

[5] Gallium Arsenide, Nano Flex POWER CORPORATION: http://www.nanoflexpower.com/gallium

- **Power management and distribution (PMAD)**

Power management and distribution (PMAD) system is used to deliver the direct current (DC) electricity generated by PV array into the microwave devices. PMAD includes of the following parts:

- electric cables
- Sliding slice (Sliding rail and pulleys)
- Conductive joins

The pulley makes a strong mechanical connection. Moreover, line contact between slide and rail reduces friction.
In order to reduce the heat dissipation the solar cells array and transmitting are designed in separate parts and not in sandwich structure. It makes it possible to obtain better concentration ratio of photovoltaic cell array. (See Figure 18, left side)

- **Wireless Power Transmission (WPT)**

There are two different methods for transmitting the generated electricity from space to the earth wirelessly. Assessment has been done for both methods of transmission: microwave beam at specific frequency and laser. Summary of evaluation is given as follows:

- **Laser Concept**

As electromagnetic signals pass through vacuum at light speed, signal high wave length means lower frequency and signal short wave length means higher frequency (Neely et al., 2013) According to Yang et al. (2016), Researchers are always concerned about scale and cost of transmitting and receiving antennas. Therefore the transmission method shall meet requirement. Evaluation result shows that the shorter wave length or higher frequency needs smaller aperture of the antenna on the Beam Collection Efficiency (BCE) between transmitting and receiving antennas. In contrast, increasing frequency results in efficiency decreasing of circuits, semiconductors and tubes. Although using of laser has the advantage of very low shortwave length which means smaller size of antenna and low cost, it is not able to pass through cloud or haze readily. This causes inefficient transmission.

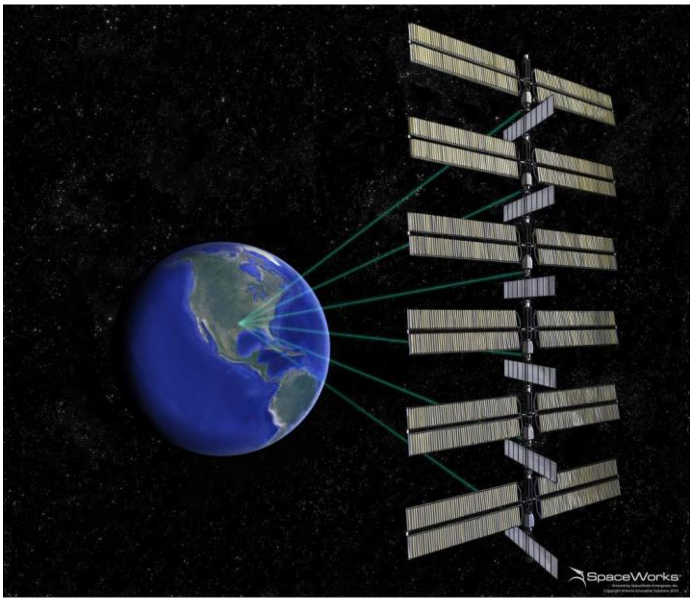

Figure 21: Laser concept (Artwork from SpaceWorks Engineering, Inc)[6]

- **Microwave Power Transmission Concept**

In contrast to laser method, the microwave power transmission (MPT) method has great advantages of ability to pass through the earth's atmosphere as well as higher components efficiency. However, when using MPT, a long antenna is required due to the high wavelength of microwave. For many years, several research and studies have been made on MPT (Yang et al., 2016). Microwave Power Transmission concept is also used in the 1979 SPS reference system (Mankins, 2009). In this regard, Japan and U.S. have done several experiments which show validity of MPT for SSPS (Mankins, 2014). According to the study, microwave frequency with limited range is appropriate for MPT to the earth surface (Yang et al., 2016). At the earth's atmosphere, the frequencies range of 2.45 GHz, 5.8 GHz and 35 GHz are in the range of microwave radio window. *"The radio window is the range of frequencies of electromagnetic radiation that the earth's atmosphere lets through. The wavelengths in the radio window run from one centimetre to about eleven-metre waves*"[7].
According to (Yang et al., 2016), in the next 20-30 years, technology development of microwave devices would make the frequency of 5.8 GHz possible. In this regard, it is obvious that heat dissipation and cost are also the key points. For OMEGA, a diameter of 1km scale of transmitting antenna is estimated, based on the orbit altitude of 36000km,

[6] Image Gallery, http://www.spaceworksengineering.com/, http://sei.aero/gallery/index.shtml
[7] Radio_window: https://en.wikipedia.org/wiki/Radio_window

frequency of 5.8GHz and relevant wave length of 5.17 cm. The size and weight of the antenna is relatively high. The antenna is comprised of around 5.3 million elements. Thus, it needs a large aperture. Such large aperture cannot be assembled and integrated in a single part. Therefore, it is planned to design it modularly. As shown in right side of Figure 18 the antenna is modularly designed and comprised of the following parts:

- Modules
- Primary sub-array
- Secondary sub-arrays

The whole antenna consists of the several secondary sub-arrays. Since researchers are always concerned about the scale and cost of SSPS, the size of transmitting and receiving antenna is to be also taken into account. The beam collection efficiency (BCE), between transmitting antenna and receiving antenna on the earth, can be calculated based on the radio wave theory.

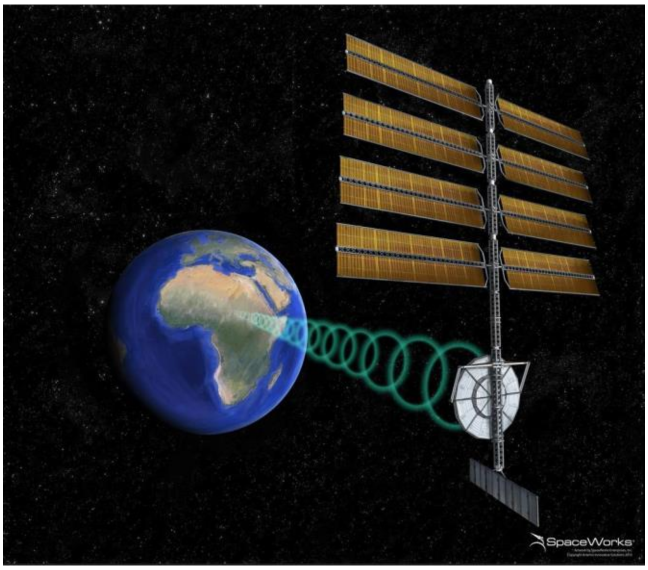

Figure 22: MPT concept (Artwork from SpaceWorks Engineering, Inc)[8]

[8] Image Gallery, **Fehler! Hyperlink-Referenz ungültig.**http://sei.aero/gallery/index.shtml

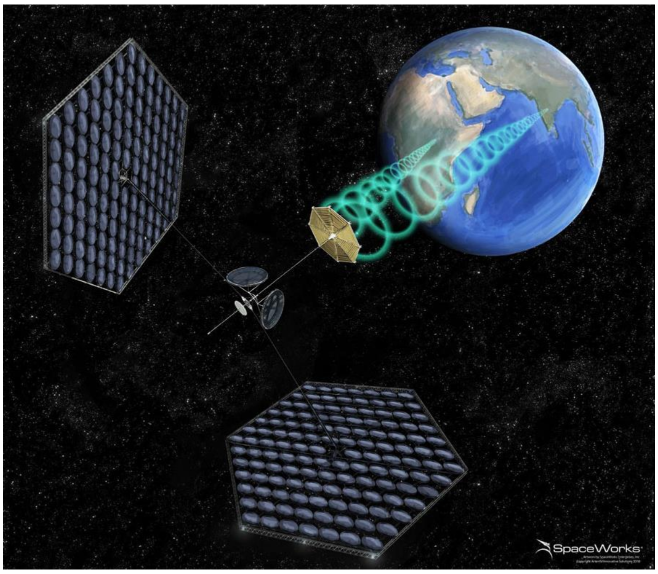

Figure 23: Modular Sandwich Microwave SPS (Artwork: SpaceWorks Engineering, Inc)[9]

- **Rectifying antenna (rectenna)**

As already mentioned, the electricity generated by PV array will convert to microwave through a radio frequency (RF) aperture and would deliver to the Earth (Jaffe et al., 2014; Yang et al., 2016). The transmitted microwave beam will be collected at the earth via rectenna (rectifying antenna) (Yang, et al., 2016). The rectenna will convert the microwave energy to direct current (DC) and will fed into the earth's power grid.

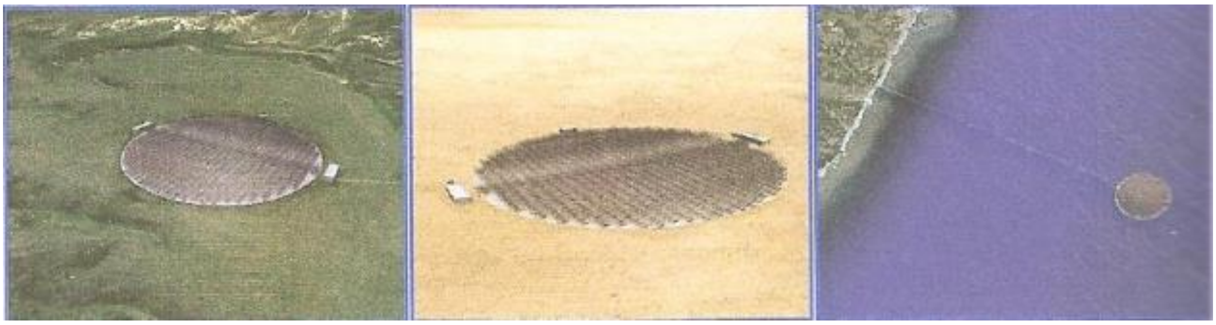

Figure 24: Rectenna on the Earth (Mankins, 2014: 154)

As Figure 24 shows, receiver on the Earth can be located in the sea, desert or green area (Mankins, 2014)

[9] Image Gallery, http://www.spaceworksengineering.com/, http://sei.aero/gallery/index.shtml

Table 5 indicates the preliminary system mass and efficiency of OMEGA which would be probably realized around 2050 (Yang et al., 2016).

Table 5: OMEGA-Summery result (Yang et al., 2016: 57)

The OMEGA scale preliminary results (2 GW @ Earth).

	Specification	Mass (MT)
Spherical collector	Specific mass goal is 0.051 kg/m^2, including thin-film reflector and skeleton frame.	~957
Solar power generation	GaAs, efficiency goal is 60% and power/mass ratio goal is 3000 W/kg	~1903
PMAD	Superconducting cables, specific mass goal is 15 kg/m.	~59
Transmitting antenna	Specific mass goal is 25 kg/m^2, including solid-state transmitters, power division network, phase shifters, antenna elements and support structure.	~19,634
Attitude control	Propulsion system with propellant.	~400
	Total	~22,953

Table 6: The OMEGA system efficiency result (Yang et al., 2016: 57)

The OMEGA system efficiency preliminary results (2 GW @ Earth).

	Current state		The OMEGA	
	Efficiency	Power (GW)	Efficiency	Power (GW)
Photoelectric efficiency	0.30	22.4*	0.60	5.14*
DC-RF efficiency	0.50	6.73	0.85	3.09
Amplitude error	0.99	3.37	0.99	2.62
Phase error	0.98	3.33	0.98	2.59
Quantization error	0.99	3.27	0.99	2.54
Antenna aperture efficiency	0.98	3.23	0.98	2.52
Propagation loss	0.98	3.17	0.98	2.47
Beam collection efficiency	0.92	3.11	0.92	2.42
Rectenna efficiency	0.70	2.86	0.90	2.22
DC		2.00		2.00
dc-dc efficiency	18.2%		47.4%	

However, by current technology, the system scale is estimated to be about 8-10 km. OMEGA needs still more advance technology to become realize (Yang et al., 2016).

- **Development in Japan**

A Commercial type of SSPS has been studied by JAPAN Aerospace Exploration Agency (JAXA). The system aims to produce 1 GW power output at 2030. Microwave and Laser method of transmission have been considered in the design and the models named M-SSPS and L-SSPS respectively. The studies focused mainly on the system concept and architecture, flight demonstration plan-making and technology development (Mori et al., 2006). The microwave and laser based models are summarized as follows:

- **SSPS – Microwave based**

According to (Mori et al., 2006), the introduced M-SSPS concept was named 2003 JAXA Reference System (See Figure 25). The system is composed of mirrors and a modular unit. Modular unit consists of solar cells and microwave power transmission antenna which are integrated into the model and used as energy conversion unit. Modular design makes it possible to assemble the system easily and automatically by robots. However, designers were concerned about thermal control system. Thus, in FY2004 some studies were made on changing the system structure for feasibility of thermal system. In the model the solar panels and microwave are separated (See Figure 26).

System scale and mass:

- *"Primary mirror: 2.5 km x 3.5 km, 1000 ton x* 2
- *Solar panels: φ 1.2 km ~ 2 km (TBD)*
- *Microwave power transmitter: φ 1.8km ~ 2.5 km*
- *Total Weight: less than 10,000 ton"* (Mori et al., 2006: 135)

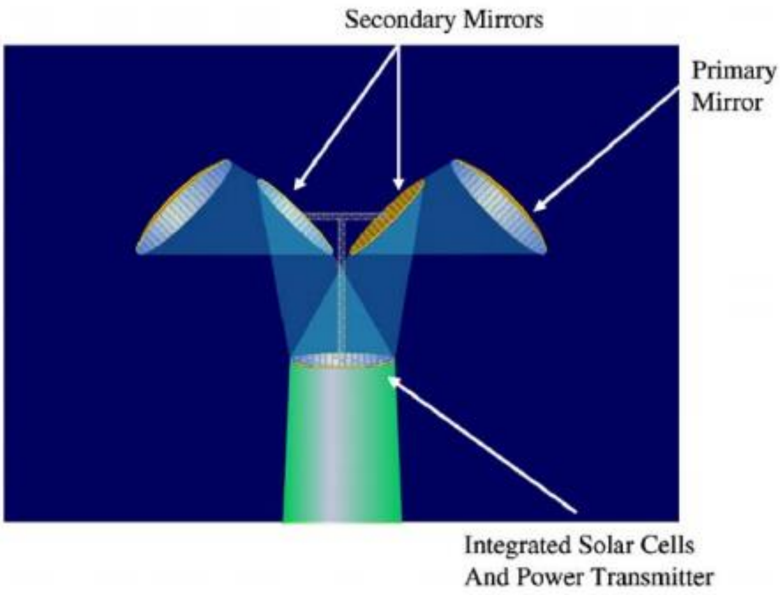

Figure 25: M-SSPS - 2003 JAXA Reference System (Mori et al., 2006: 135)

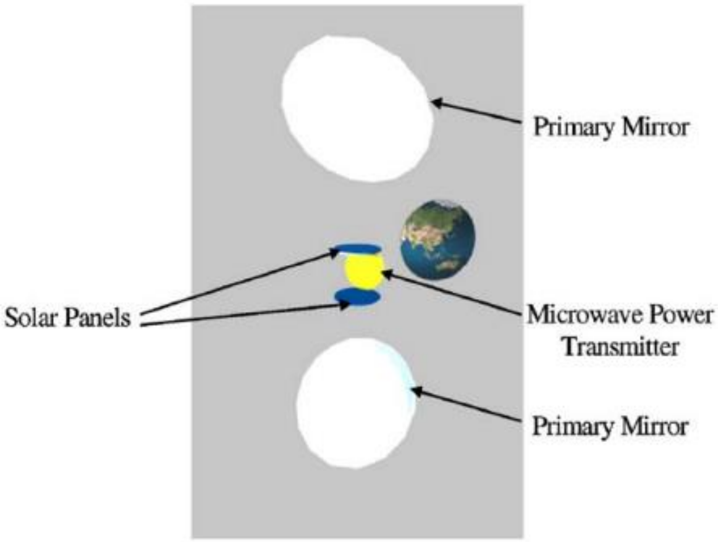

Figure 26: M-SSPS - 2004 JAXA Reference System (Mori et al., 2006:135)

- **SSPS – Laser based**

According to Mori et al. (2006), the system consists of solar condenser mirrors or lenses and laser generator. Solar condenser focuses sunlight. Generated solar energy transmits to laser generator. Laser beam would be sent to a hydrogen generating device on the earth for producing hydrogen from seawater. Hydrogen generating device is located on an ocean.

Laser based SSPS has a high potential to meet the continuously increasing world's hydrogen energy demand which dependence on fossil-fuel (see Figure 27)

Based on the mentioned concept, "A base unit" was considered (See Figure 28). *"A base unit consists of solar condenser mirrors, radiators, laser generator, laser beam irradiator and support structures"* (Mori et al., 2006: 135). A most qualified candidate for Laser medium can be crystal type of Neodymium doped yttrium aluminium grant (Nd: YAG).

"A base unit" is estimated to produce power in 10 MW class and consists of the following major parts:

- *"Primary solar condenser mirrors: 100 m x 100 m x 2*
- *Radiator: 100m x 100m x2"* (Mori et al., 2006: 135)

System is expected to generate amount of 1 GW power. The system is composed of series of "A base unit" which are vertically connected. (See Figure 29)

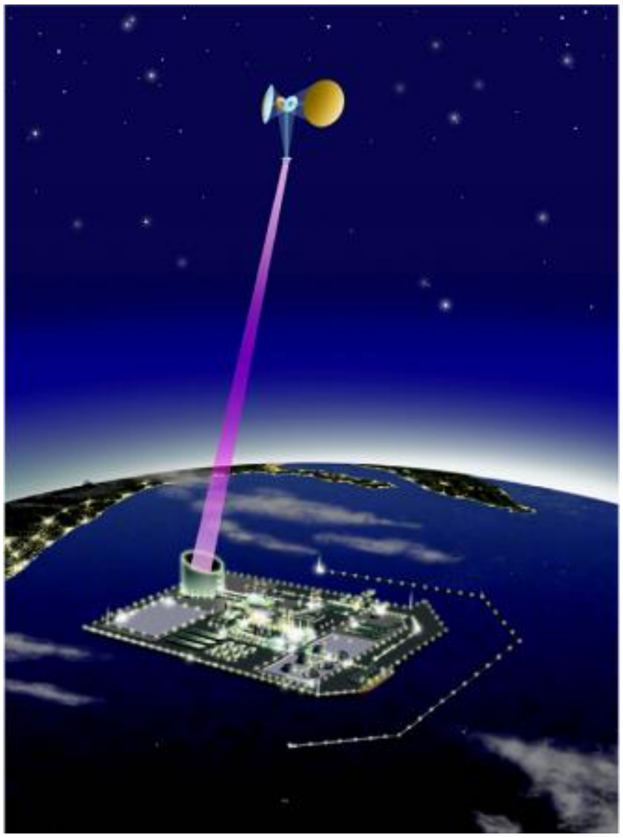

Figure 27: SSPS Concept - laser-based (Mori et al., 2006: 133)

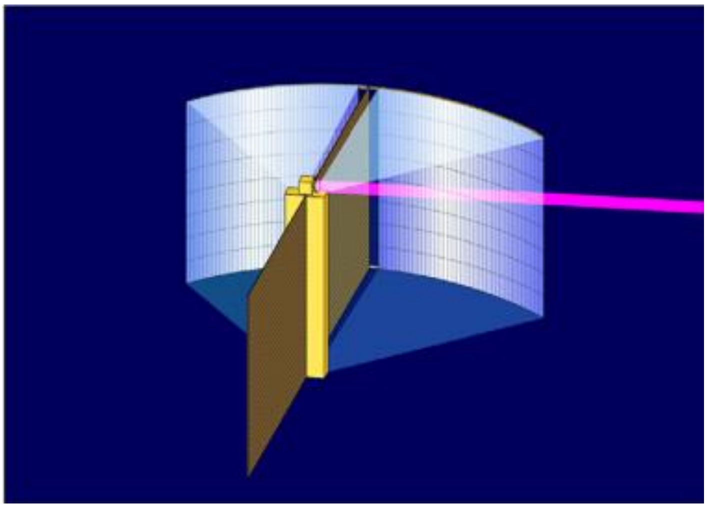

Figure 28: One base unit - L-SSPS (Mori et al., 2006: 135)

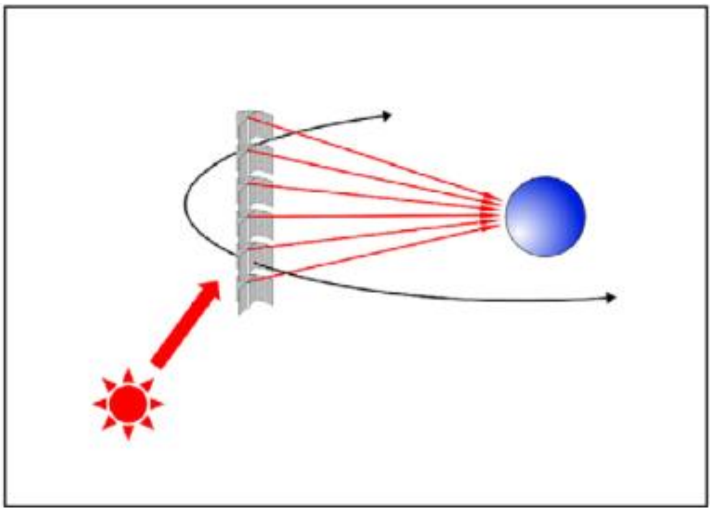

Figure 29: L-SSPS concept - 1 GW class (Mori et al., 2006:136)

Also, study has been made on critical factors such as conversion efficiency and thermal control feasibility. Feasibility study has been also made on system's earth device as well as using laser beam for producing hydrogen. These studies and past experiences resulted in promising a high efficient electric power generation technology using solar cell and laser.

System cost evaluation and environmental impacts have been also done by researchers by use of a created life cycle model (See 3.3.5).

Also, JAPAN Aerospace Exploration Agency (JAXA) has an stepwise approach to build a commercial SSPS aiming to produce 1 GW power operating in GEO till 2030 (Mori et al., 2006). (See Figure 32: JAXA - SSPS Roadmap of JAXA (Mori et al., 2006: 134), section 3.4 Future perspective).

As Mankins (2014), discussed, although work on SPS has been slowed due to the earthquake and tsunami on March 11, 2011 near Tokyo which resulted in reducing budget for SPS R&D, use of renewable energy become clearer. Therefore work on SPS has continued from past years (to 2013). Moreover, Space Solar Power is projected to be included in Japan's space program according to restructured "Basic Space Law" of japan (January 2013).

- **Development in China**

According to Mankins (2014), currently china makes significant efforts on SSP. In the recent years, there are a number of SSP in China. Today, China focused on their internal R&D research on SSP and also on some international research. However, many years age, some international group such as Switzerland based, European company, the "Space Energy group" (SEG) were involved in SSP activities in china. These groups seem to be no more involve in SSP recent activities in china.

- **Development in Europa**

ESA, after some years break, makes a new effort to revise SSP with respect to the "20-20-20" Energy policy of the European Union (Mankins, 2014).

3.3.2 Technological barriers

The fundamental technological barriers exit currently and – is expected to be overcome– in the future due to technology development and research progress in the field:

- More advance technology (Yang et al., 2016)
- System material, scale and mass (Mankins, 2009; Yang et al., 2016)
- Solar cell material and reduction of module area (Pandey et al., 2016)
- Transportation from Earth to Space and transportation in space (Keith Henson, 2010; Mankins, 2014; Yang et al., 2016)
- System scale and mass (Mori et al., 2006; Mankins, 2014; Yang et al., 2016).
- Size of rectenna (Yang et al., (2016)
- Environmental adaptability in space (Yang et al., 2016)
- Large system assembly (Mori et al., 2006; Mankins, 2014)

3.3.3 Energetic appraisal

As already mentioned, according to the scientists, sun is the largest available potential energy source. As Hosenuzzaman et al. (2015) mentioned, the sun power on the surface of the earth is around 1.4 x 10^5 TW. According to Mankins (2014), the Sun energy in space near earth is amount of 1, 368 W/m². SSPS is unaffected by diurnal cycle, atmospheric and weather condition. Therefore, SBSP is expected to provide base load power for terrestrial markets.

As an example, the recent Model OMEGA is expected to supply 2 GW on the earth around 2050 (Yang et al., 2016).

3.3.4 Energetic barriers

The fundamental energetic barriers exit currently and – is expected to be overcome– in the future due to technology development and research progress in the field:

- System efficiency (Mankins, 2014)
- Solar cell material and cell efficiency enhancement (Pandey et al., 2016)
- Environmental adaptability in space, e.g. device efficiency at high temperature (Yang et al., 2016).

3.3.5 Environmental appraisal

The environmental impact assessment can be generally done by using an analyzing tool called life cycle analysis (LCA). LCA assesses the system environmental impacts related to all stages from cradle to grave. Assessment will be done for stages such as raw material extraction, manufacturing, use, maintenance, repair and recycling. LCA has been standardized by International Organization for standardization (ISO) specified by ISO numbers 14040 and 14044. (Durrieu & Nelson, 2013). As per the ISO 14040/14044:2006, 4 phases are defined for process of LCA requirements as follows:

- *"Goal and scope definition*
- *Life cycle inventory (LCI)*
- *Life cycle impact assessment (LCIA)*
- *Interpretation"* (Chatzisideris et al., 2016: 2)

"The European Space Agency (ESA) is currently developing an LCA tool that will facilitate implementation of LCA studies for some of its missions. And *ESA intends to generalize the*

use of such approaches in the European space activity sector" (Durrieu & Nelson, 2013: 249).

As Mankins (2014) discussed, with regard to "green" energy, SPS would be a solution. By comparison with other sustainable energy sources, SPS has less environmental impact during fabrication. Moreover, SPS energy payback is reasonable. Furthermore, With regard to global temperature, some SPSs are analyzed. For example analyzing of single SPS 1.5 GW showed that, less than 0.000001 °C would arise when deliver this power to the Earth. By comparison, global emission from power generation and transportation is considerable. Nevertheless, detailing of the SPS environmental impact is to be pursued by next efforts.

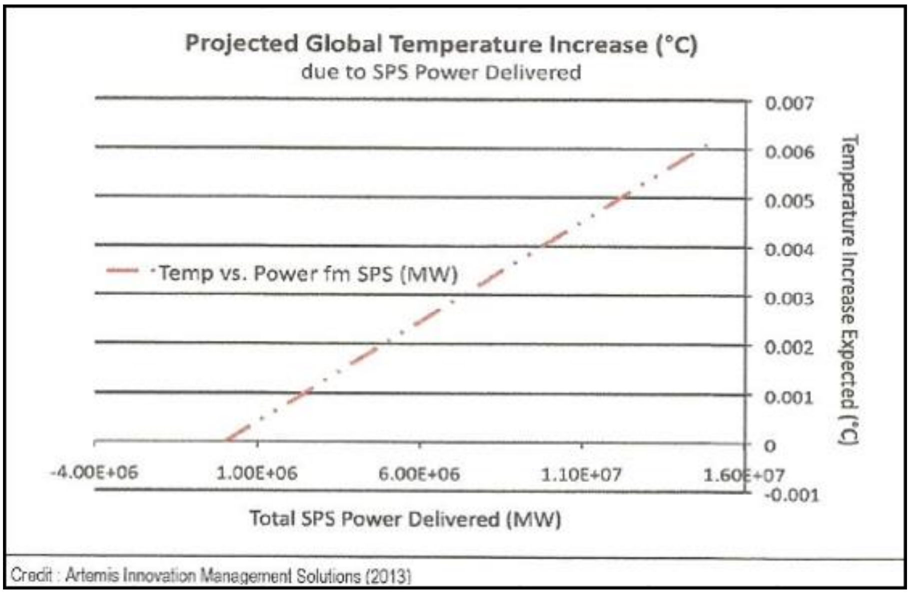

Figure 30: SPS- Global temperature increase (Mankins, 2014: 291)

According to the researched data, some SSPS environmental impacts are briefly described as follows:

- **Environmental impact due to CO_2 emission**

With respect to CO_2 emission, SSPS is an environmental friendly system which releases low carbon dioxide into the environment. (Mori et al., 2006). Table 7 and Table 8 shows CO_2 emission and energy payback time of 1 GW commercial SSPS. These tables are based on the created life cycle model by JAPAN Aerospace Exploration Agency (JAXA) with regard to commercial SSPS. (Mori et al., 2006).

Table 7: CO_2 emission - SSPS 1GW power output (Mori et al., 2006: 137)

To manufacture the space segment	89,062	t-CO_2
To lift it into space	983,400	t-CO_2
To manufacture the rectenna	1,405,113	t-CO_2
To operate the space segment	32,147	t-CO_2/yr
To operate the rectenna	14,051	t-CO_2/yr

SSPS will release amount of 12.22g of CO2 into the environment by producing of 1kWh of electricity (Mori et al., 2006).

Energy payback time achieved by SSPS is higher than amount by busting coil, LNG (Liquefied natural gas) and nuclear power generation systems (Mori et al., 2006).

Table 8: SSPS - Energy payback time (Mori et al., 2006: 137)

Energy payback time requires for SSPS

Energy invested to manufacture the space segment	1682	GWh
Energy invested to lift it into space	2204	GWh
Energy invested to manufacture the ground segment	1706	GWh
Energy to keep the space segment operating	117	GWh/yr
Energy to keep the ground segment operating	17	GWh/yr
Total invested energy	10,805	GWh
Total energy return on investment	350,400	GWh
Energy return on investment	32.43	
Energy payback time	1.23	yr

- **Environmental impact due to Space debris**

Space debris is continually increasing due to space development. Space debris can damage space crafts. *"Space debris is made up of non-functional satellites (23%), upper stages of launchers (18%), functional debris (14%), e.g. bolts, belts, and fragments (45%) originating from collisions, launcher upper stages and spacecraft explosions"* (Durrieu et al., 2013: 240). Catalogued debris greater than 5-10 cm in size are located in LEO and debris between 30 and 100 cm size in GEO. Assumed amount of non-catalogued are based on the sources. The number of 16000 debris tracked by US Space Surveillance Network while is yearly increasing by several hundreds, According to French Space agency (CNES), there are number of around 200.000 debris with 1-10 cm in size and around 35.000.000 with 0.1-1 cm. In LEO, roughly 40% of debris are larger than 1mm in size. One of the discussion related to space is collision risk. Collision, due to space debris, can occur on orbit or on people when debris return from space into the earth. In LEO, Satelellite explosion occurs if it collides with a piece of debris greater than 10 cm. It is to be taken into account that debris between 1 and 10 cm in size cause higher damage because of Kinetic energy (Durrieu et al., 2013). Figure 31 shows space debris in LEO.

Therefore, debris objects must be removed from space. Debris capturing and disposing seems to be a practical solution to clean earth orbit. In this regard, there is a technology which is named Active Debris Removal (ADR). moreovere, wide range of conceptual studies have been already made on this field as well as on ADR demonstration in earth orbits (e.g. mission baseline and EC FP7 RemoveDEBRIS mission). Revising the mission base line led to the RemoveDEBRIS mission which is a low cost mission aming to demonstrate the ADR technology due to a targeted lunch in 2017. Furtheremore, Some clean space roadmaps have been prepared by ESA aimining to focus on space orbit mitigration and to provide technologies for space debris remadiation. Currently, ESA focuses on removing of very heavy pices of debris with several tonnes in size (Forshaw et al., 2016).

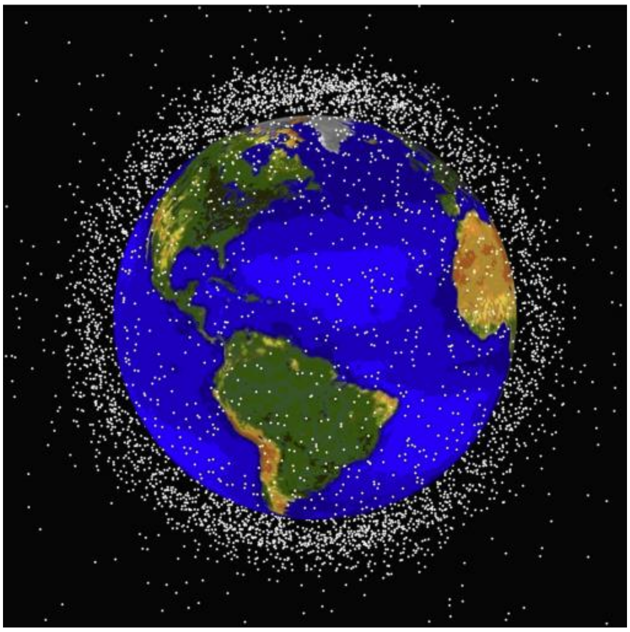

Figure 31: Space debris in LEO (Durrieu et al., 2013: 241)

- **Environmental impact due to Launch**

Launch can cause some pollutions for Earth's environment such as following (Durrieu et al., 2013):

- Pollution which come back to earth during accelerator stage. It occurs after fuel exhaustion.
- Pollution due to propellant type which is depend on launch vehicle engine
- Releasing debris and chemical components into atmosphere during launches and re-entries

Launch can also causes local impacts. As an example, French Guiana Space Center (CSG) took 600 measurements of hydrochloric acid (HCL), nitrogen dioxide (NO2), hydrazine and alumina at different distances from launch site. The measurements indicated a high level of hydrochloric acid and alumina concentrations mostly on the Launch area less than 2.3 km.

Table 9: Example of Launch environmental impact (Durrieu et al., 2013: 241)

Example of maximal concentrations of HCL and alumina measured during an Ariane 5 launch (flight 185, August 24, 2008). Near field refers to a distance from launch site <2.4 km and far field from 2.4–24 km. Measures are compared to human toxicity thresholds (source: http://www.ggm.drire.gouv.fr/).

	Maximal near field concentration (mg/m^2)	Maximal far field concentration (mg/m^2)	Toxic limits defined for humans
Ion CL – (HCL)	5136.2	89.84 (measured at 4.35 km)	90 mg/m^3: irreversible effect after 30 min exposure, 700 mg/m^3: lethal effect after 30 min exposure
Alumina	94.68	3.49	Acceptable mean exposure value for workers = 10 mg/m^3 during 8 h, 5 days/week

- **Environmental impact due to Launch malfunction**

According to lessons learned IAEA (2012), there is a risk of nuclear critically emergencies. If Launch fails to access to space, nuclear or other chemical products will re-enter to the atmosphere. (see Table 10)

Table 10: Radiation Emergency (Lessons Learned IAEA, 2012: 89)

No.	Year	Country	Vehicle type	Location	Identifying name	Cause and consequences	Ref.
				Space vehicle			
19	1964	USA	Spacecraft	West Indies Ocean	SNAP-9A Transit-5BN3	Satellite containing 630 TBq of 238Pu failed to achieve orbit and vaporized during re-entry in the southern hemisphere	[123]
20	1968	USA	Spacecraft	Santa Barbara, California	Nimbus BI	Spacecraft failed to achieve orbit; 2 RTGs recovered intact	[123]
21	1970	USA	Spacecraft	South Pacific	Apollo 13	Malfunction in oxygen supply led to emergency return to earth in the lunar landing module; an RTG onboard entered intact and is at a depth of not less than 6000 m in the Tonga Trench	[123]
22	1978	USSR	Spacecraft	Northern Canada	Cosmos 954	Research satellite carrying small nuclear reactor re-entered atmosphere and spread radioactive fragments over wide area	[123]
23	1983	USSR	Spacecraft	South Atlantic	Cosmos 1402	Satellite failed to boost nuclear reactor into higher orbit after completion of mission; reactor core and fission products re-entered atmosphere east of Brazil	[123]
24	1996	USA	Spacecraft	Pacific Ocean	Mars 96	Unsuccessful burn of booster resulted in re-entry of earth's atmosphere west of Chile; 18 RTGs onboard with total 238Pu activity of 174 TBq	[123]

- **Environmental impact due to Wireless Power Transmission**

According to Mankins (2014), High power will be emmited in space due to SPS WPT transmitter which causes interference with other systems. Harmful interference due to SPS WPT in space or on Earth shall be avoided. At present, WTP R&D has mostly focussed on ISM RF bands which is considered by International regulatory agreement for use in ISM (Industrial, Scientific, and Medical (RF Bands)) application. In this regard, SPS R&D shall be coordinated with national and international organisations such as ITU (International Telecommunication Unit).

3.3.6 Environmental barriers

The environmental barriers exit currently and – is expected to be overcome – in the future due to technology development and research progress in the field. Some key barriers are as follows:

- Risk of nuclear critically emergencies (Lessons Learned IAEA, 2012: 89) as described in 3.3.5, Environmental impact due to Launch malfunction.
- Space debris, e.g. related to decommissioning, some parts may stay in orbit (Durrieu et al., 2013).
- Safety concern for human and environment, e.g. Wireless power transmission electromagnetic interference. More R&D is essential (Mankins, 2014).

- Detailing of the SPS environmental impact is to be pursued (Mankins, 2014).
- Releasing debris and chemical components into atmosphere during launches and re-entries (Durrieu et al., 2013).

3.3.7 Economic appraisal

The key factors for any business case, including SBSP, are return on investment and risk. Investing in space based solar power implies a high investment risk, because the technology is still at research level and in development and requires a high and long term investment. What are the major factors for a business case of SBSP?

- **High potential**
  - High level of power production (Mankins, 2014)
  - High efficiency through optimal use of solar energy and technology development. (See also 3.3.3 energetic appraisal)
- **High risk**

  Considering the barriers, realizing SSPS means high risk is to be considered:
  - At research level and still in development (Yang et al., 2016)
  - Demanding high Technology (Mankins, 2014)
  - High investment cost due to system scale and system cost (Mankins, 2014; Yang et al., 2016)

According to Mankins (2014), the most important economic challenges for realizing Large Space Solar Power are: System hardware cost, cost of hardware transportation from Earth to orbits and operation & maintenance cost. Moreover, there are also some other challenges such as efficiency enhancement of solar energy conversion, cost efficient and effective WPT. Currently, with regard to transportation from Earth to its orbits, there are some solutions as following:

- **Transportation from Earth to orbit**

System concepts of reusable launch vehicle seems to be a solution for Earth-to-Orbit (ETO) to LEO (cost around $500 to $1,000 per kilogram). These prices are affected by achieved launch rates. In this regard, more study than those by IAA (2008-2011) and by NIAC (2011-2012) is still essential. However, the current launch vehicles are not sufficient for transportation in space from LEO to GEO. Reusable launch vehicle in space seems to be possible due to ethnology development.

According to Keith Henson (2010), replacing fossil fuel by SBSP can be possible by sale price of 1-2 cent/kWh and amount of ~ $100/kg for lunch cost to GEO. To reach this amount, transportation of 100 tonne per hour is required. For this purpose, transportation in two stages to GEO is proposed. In first stage a Slylon-rocket-plane makes 5 km per sec and in second stage a laser stage makes 6.64 Km per Sec. This combination makes lunch cost under $100/kg and transportation of around 1 million tonnes per year. So, 200 GW of power per year would be possible. Moreover, a Pro Forma business case showed a **~ $65 B profit** after **25 years** where the **2 TW energy** per year reached.

Also, as an example a cost evaluation is given bellow (According to Mori et al. (2006)) for 1 GW microwave-based SSPS (JAXA 2004 reference model).
Cost calculation was done for system manufacturing, construction and operation considering:

- Major parts in the space: Primary mirrors, solar panel, microwave power transmitter, radiator and necessary support structures
- Major parts in the Earth: Rectenna, microwave collecting part, support structure and connecting to the earth's energy grid
- Launch cost consist of transportation cost of RLV (Reusable Launch Vehicle) to LEO and from LEO to GEO by OTV (Orbit transfer vehicle)
- Maintenance cost consists of construction cost in space as well as in the earth.

Cost evaluation has been done based on considering estimated total mass of space segments (9907 ton) and microwave power transmitter of 1.8 km in size. Calculation shows: total cost of **$10.7 billion** for **1 GW** microwave-based SSPS and the amount of **7.8 cent/kWh** for power generation cost. However, it has to be taken into account that the total cost is calculated based on the current (2006) input parameter values. Therefore, the parameters must be revised in the future when system might be realized in the next 20-30 years. In 2006, the system life was estimated to be about 40 years.

3.3.8 Economic barriers

Some of the fundamental economic barriers exit currently and – is expected to be overcome in the future. However, according to Mankins (2014), the economic barriers are also depends strongly on the progress in research and technology development in the field. Some of the fundamental barriers described below:

- High investment cost due to system scale and system cost (Yang et al., 2016).

- Cost of transportation to space and transportation in space: High speed transportation needs high cost launch fuel due to problem of space access including cost of earth to orbit transportation and orbit to orbit transportation in space, while low cost launch fuel causes long low launch thrust and long transportation time (Mankins, 2009).
- Transportation from Earth to Space and transportation in Space (Keith Henson, 2010; Mankins, 2014; Yang et al., 2016).
- System installation cost (Mankins, 2009).
- According to Mankins (2014), the most important economic challenges for realizing Large Space Solar Power are: System hardware cost, cost of hardware transportation from Earth to orbits and operation & maintenance cost. Moreover, there are also some other challenges such as: solar energy conversion shall be efficient, wireless power transmission shall be cost effective, etc. "*Of these, the high cost of space hardware is the single barrier to affordable space missions*" (Mankins, 2014: 183).
- High cost of GaAs material and manufacturing of solar cell (Tyagi et al., 2013).
- Cost of rectenna (Yang et al., 2016).
- High cost of system assembly, integration, management, operation and maintenance crews, e.g. assembly crews up to about one hundred people (Koelle, 2000)

3.4 Future perspective

As already mentioned in 3.3 according to Mankins (2014), currently, SSP has continuing progress in Japan and China. These two countries have a strong interest in strategic planning for their future energy demand. In this section, future perspective of some SSP is briefly described based on the researched available update sources.

3.4.1 Technological and Energetic Perspective

As of today, in the US, the OMEGA concept is the most improved technical SSPS but is still at an experimental stage. More technology improvement and cost reducing are the major points to make it realize in the future. However, researchers are still concerned about system optimization. System mass, energy distribution and system cost are the key points which to be studied more. Furthermore, high investment is still needed to make it commercially realize. The OMEGA is projected to supply of 2 GW power into earth's power grid system and might be realized around 2050. As of today technology, solar power collecting of 22.4 GW is estimated. The system scale of 8-10 km is estimated. However, it seems to be an unrealized aim because of technology and cost. Promising advanced technology may make it realize (Yang et al., 2016).
Also, JAPAN Aerospace Exploration Agency (JAXA) has a stepwise plan to build a commercial SSPS in 1 GW power level, operating in GEO, till 2030 (Mori et al., 2006).

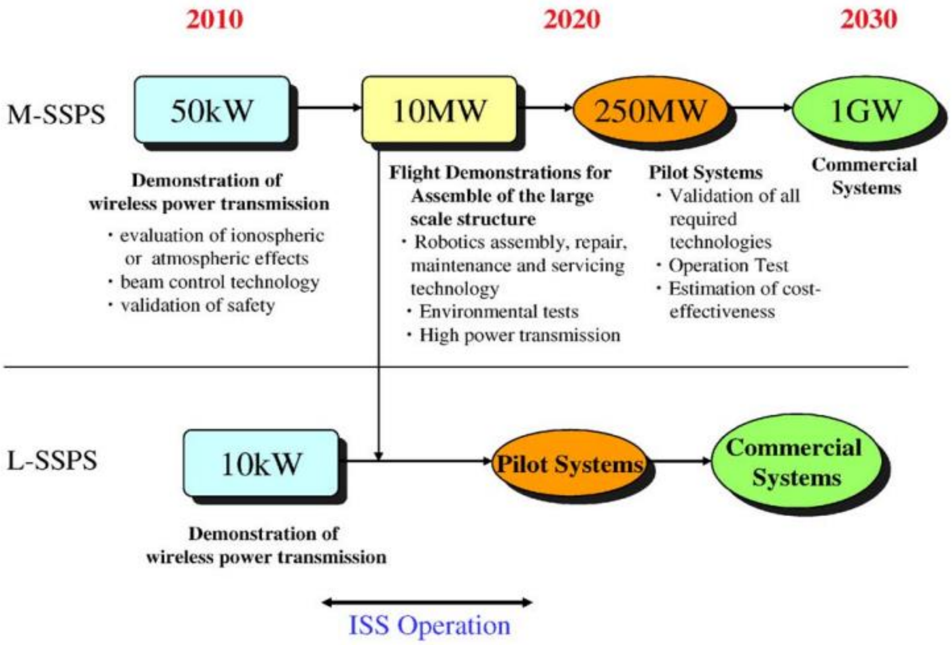

Figure 32: JAXA - SSPS Roadmap of JAXA (Mori et al., 2006: 134)

Also, according to Mankins (2014), in 2010, EADS Astrium - the largest aerospace company, investigated in WPT GEO satellite demonstrator (10kW delivered laser) aiming to provide power to ground by 2020. In this regard, several new technologies would be required.

Also, according to Mankins (2014), currently china makes significant efforts on SSP.

3.4.2 Electricity market perspective

With regard to SSP electricity market, as Mankins (2014) mentioned, in future, sustainable energy sources (particularly solar and wind) are projected to have more share in global energy mix due to the policy of using of low carbon energy technology. In this regard, a market assessment has been done for SPS-ALPHA based on the German government's 2000-2010 FIT solar power. It includes the following stages:

- *"Years 0-8 FIT up to ~ 40¢ - 50¢ per kWh;*
- *Years 0-8 FIT up to ~ 20¢ - 25¢ per kWh; and;*
- *Years 0-8 FIT up to ~ 15¢ - 20¢ per kWh"* (Mankins, 2014: 356)

As Mankins mentioned: *"With various technologies*, *beyond the first 20 years*, *energy from SPS-ALPHA should be able to deliver baseload power at competitive prices without incentives"* (Mankins, 2014: 356).
Also, Mankins (2014) reviewed the present electricity market aiming to know if SSP can be a competitive market. According to his review, typical electricity cost per kWh is in range about 5¢ to 10¢ in many markets. This range is also dependent on the involved technology. However, based load electricity cost is higher in some markets, e.g. islands or remote regions (around 10¢ to 20¢ per kWh or more). SPS-ALPHA economic analysis shows that, it is possible to deliver base load power from SPS_ALPHA in global earth markets at less than 10¢ per kWh (a levelized cost of electricity (LCOE)) from 15-20 years. Therefore, SPS is able to be competitive with markets – even with the present markets. Currently, cost of power in space is around $50 - $100 per kWh. SPS would become realize by reducing this cost to less than 10¢ per kWh and cost of transportation to space to less than $500 per kilogram.

3.4.3 Policy perspective

As Mankins (2014) discussed, future challenges of Solar Power Satellites include not only technical challenges but also policy challenges for SPS development. In this regard, the following subjects are to be considered:

- Space policies

- Energy policies
- Environmental and climate related rules
- Technology research and development (R&D) program plans and international technology transfer restrictions
- Policies concerning tax and/or incentives vis-à-vis space development or energy
- Defense and security issues
- Various factors related to the regulatory environment
- International relations and related concerns

In this regard, many efforts have been made. As an example, in 1959, the committee on the Peaceful Uses of Outer Space (COPUOS) was established by the UN General Assembly which promoted international cooperation. Furthermore, legal frameworks is developed by COPOUS for addressing problems which may arise due to use of outer space.

As Mankins (2014) discussed, In Japan, it is projected to include Space solar power in Japan's space program due to the recent restructured "Basic Space Law" of japan (January 2013).
Also, ESA, after some years break, makes new effort to revise SSP with respect to the "20-20-20" Energy policy of the European Union (Mankins, 2014).

4 Analysis of Earth Based Solar Power (EBSP)

4.1 Method of approach

In order to give a clear overview of the current status and future perspective of the Earth based Solar Power (EBSP), the latest available data are investigated considering historical background of EBSP development, technological, energetic, environmental, economic aspects and related barriers. Since the state of the art SBSP is photovoltaic based, in order to make a reasonable analysis and comparison, the earth photovoltaic based solar power generation is compared to it.

Historical background: The history of EBSP development during the last decades is described.

Current status:

- **Technological appraisal:** The recent concept design of earth photovoltaic based power generation is described as well as state of the art technologies which are currently used in system design.
- **Energetic appraisal:** Availability of sun energy at the earth is discussed as well as system installed capacity and system efficiency of the earth photovoltaic based power system.
- **Environmental appraisal**: EBSP environmental impacts are described. LCA (Life Cycle Assessment) is discussed based on the relevant researched literatures.
- **Economic appraisal**: Current status and future perspective of earth photovoltaic based power generation in market are analyzed.
- **Relevant barriers**: With regard to the four mentioned appraisals, barriers are considered and presented.

Future perspective:

The future status of earth photovoltaic based power system is described based on the relevant researched literatures and available data.

4.2 Historical background of EBSP development

Technology of Solar Power is the result of a long term usage of the sun energy through the history of mankind. Solar energy has been used for several thousand years in different forms for cooking, heating, lighting and etc. Today, solar energy has a wide range of use. It is also used to generate electricity. One of the method to produce electricity from sun power is converting sunlight to direct current through solar cell.

The history of solar cell comes back to French physicist, Alexandre-Edmond Becquerel (1820 – 1891). Photovoltaic effect has been discovered by him. Later in 1839, his invention become the basis of solar cell (Fechner, 2015). In 1954, American Bell laboratories developed the first silicon solar cell (Hosenuzzaman et al., 2015). As already mentioned in section 3.2, oil crisis during 1970s led scientists to study on the most efficient use of high potential solar energy.

Today solar energy, on the earth is used through solar thermal by use of solar collectors, heaters, dryers, etc. and solar electricity via photovoltaic (Pandey et al., 2016).

4.3 Current status

In this section the current status of the earth Photovoltaic based solar power generation will be briefly reviewed and assessed from technological, energetic, environmental and economic perspectives as following:

4.3.1 Technological appraisal

Photovoltaic can directly convert solar radiation into electrical energy. Photovoltaic system has simple design and is easy to maintenance (Kaltschmitt et al., 2007; Pandey et al., 2016). The state of the art technical basis of photovoltaic power generation is briefly described below:

- **Technical basis*:***

Photovoltaic power generation consists of the major elements such as solar cell, batteries, inverters, charge and discharge controller, solar tracking control system and other components which are briefly described below (Hosenuzzaman et al., 2015; Kaltschmitt et al., 2007).

- **Solar cell**: Solar cell is the smallest unit in PV system and consists of two or more thin layers of semiconductor material (e.g. silicon, gallium arsenide). Solar cell works based on the photovoltaic effect which has been discovered by French physicist

Alexandre-Edmond Becquerel in 1839. Photovoltaic effect occurs when semiconductor material exposes to the light. When photons of light hit and absorbed to a semiconductor material, pairs of electrons and electron holes will be created. Then electron and electron hole move together towards the P-N (Positive – Negative) junction. When the pairs come near to the P-N junction, electric current will be generated. In order to reach a desired electric capacity, it is necessary to connect number of cells together which called solar modules and further solar panel (numbers of modules) and solar arrays (numbers of panels).

- **Batteries**: Batteries are necessary for a continuous supply of solar energy. Batteries are used for loading electricity which produced by PV power generation system.
- **Charge and discharge controller**: Controllers are necessary to prevent battery overcharge and over discharge and to make a safe and reliable operation.
- **Inverter**: Solar generators and batteries supply Direct Current (DC) which is suitable for applications which need DC supply (e.g. watches and calculators), while many others requires alternating current (AC). Inverter uses to convert DC to AC, based on the requirements (e.g. 230 V of 50 HZ, 120V of 60 HZ).

According to Fechner (2015) Photovoltaic system can connect to public grid – typically low and medium voltage system, e.g. up to 80% of the installed PV capacity in Germany is connected to low voltage system (400 V 3-phase).

- **Solar cell type and efficiency**

Nowadays, there are different types of solar cells available in the market or in R&D stage as described below (Fechner 2015).

- Mono crystalline silicon: For commercial use, modules reached approximately 15% efficiency. This type is relatively expensive due to techniques of manufacturing process.

- Poly crystalline silicon: For commercial use, modules reached approximately 14% efficiency. This type is cheaper than monocrystalline due to simpler processing techniques.

- Gallium Arsenide (GaAs): This type are often used in concentrator system and space solar power. Research cell efficiency - *GaAs* multifunction type has reached over 30% efficiency.

- Amorphous Silicon (a-Si): This type are often used for solar watch, calculator as well as in building integrated system.

- Cadmium Telluride (CdTe): This type is a thin film polycrystalline material. Production modules of this type reaches around 11% efficiency.

- Integrated Thin Film Technology, Copper Indium Diselenide (CuIse2, or CIS): This type is a thin-film polycrystalline which has reached a research efficiency of 17.7%.

- Organic dyes and organic polymers: These type are still in research and development (R&D) stage.

One of the important parameter to put the solar cell in the market is cell efficiency. Recently, researchers are continuously studying on solar cell efficiency enhancement. Today, High efficiency improvement has shown for mono crystalline silicon during the times from 15% in 1950s, 17% in 1970s and now over 28%. Polycrystalline silicon reaches 19.8% efficiency. Furthermore, silicon supply is highly available on earth and easy to extract (Tyagi et al., 2013). However, for commercial use, mono crystalline achieved approximately 15% and poly crystalline 14% of efficiency (Fechner, 2015).

Until now, mono and polycrystalline silicon are the most produced and used solar cell type in market due to its high efficiency. Market analysis shows that mono and multi crystalline type has a 90% share of total PV technology market (Tyagi et al., 2013). Although, crystalline semiconductors viz. Si and GaAs are the highest performance solar cells types, the cost of these types are higher than the other available types in the market. However, lower solar cost cell are normally made from less pure material which cannot reaches high performance (e.g. polycrystalline, amorphous inorganic or organic material or combination of both). It is why, researcher are still investigating in other alternatives aiming to reach higher performance for electricity producing. Figure 33 shows the best cell efficiencies till 2015. Thin film technology seems to be a potential alternative for mono and poly crystalline with respect to weight and cost but its low efficiency is still a problem needs to overcome. In recent times, experimental works has been done in order to enhance the efficiency of thin film technology. In this regard, different material such as CdS/CdTe and CIS have been studied. However, there are some environmental impacts related to these material. Alternative can be polymer and or organic materials. Today, organic cells are favorable to use due to low manufacturing cost, low weight, transparency property, mechanical flexibility and environmental-friendly. However, organic cells reached lower efficiency than other types. Approximately 8% efficiency has been reported for organic cells (Pandey et al., 2016). Polymer type has many advantages with respect to weight, cost and environmental impact. However, Low efficiency (around 4-5%) is still a problem (Tyagi et al., 2013).

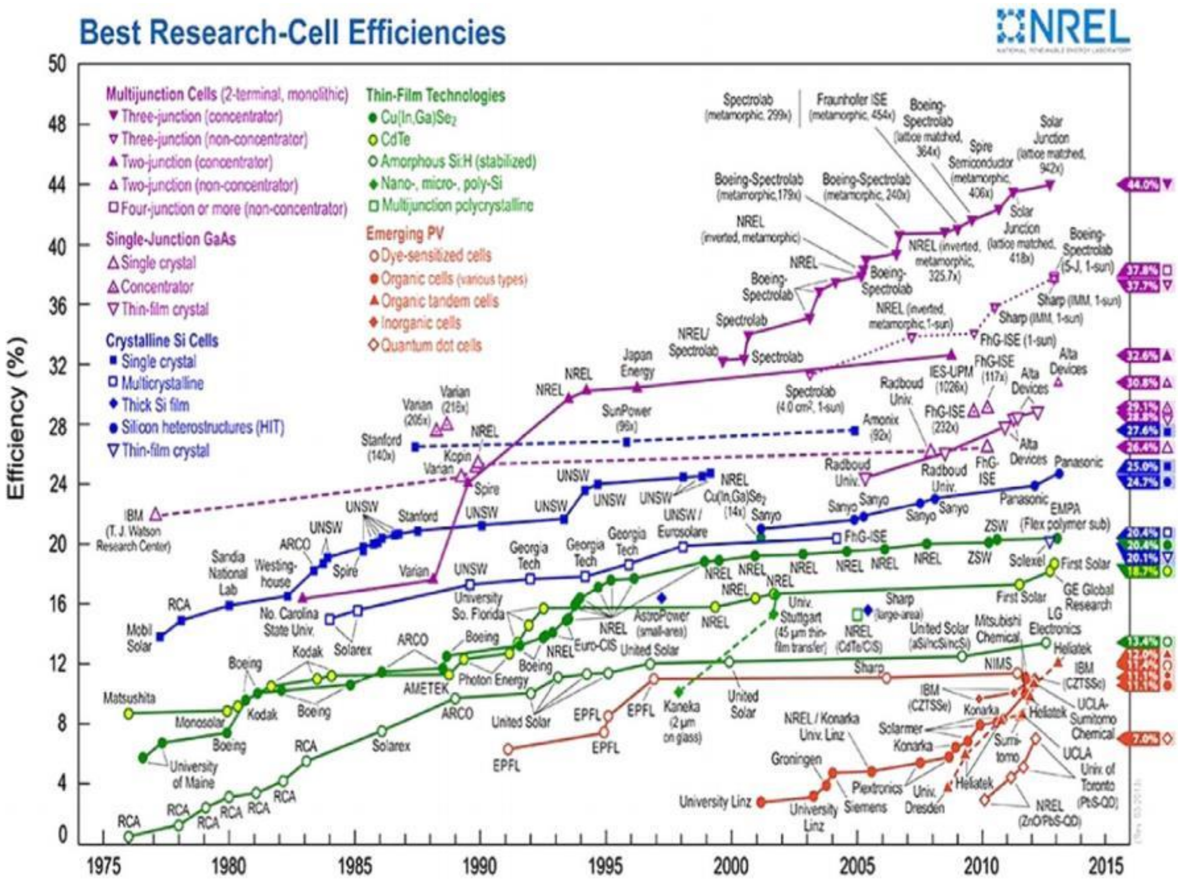

Figure 33: Best research cell efficiency (Pandey et al., 2016: 861)

As previously mentioned in 4.3.3, sun availability on the earth is very dependent to day and night cycle, seasons, climate changes and etc.

Sun radiation has a great effect on operation of power generation system (Hosenuzzaman et al., 2015). Efficiency of PV module will increase when solar irradiance increases. That makes it possible to hit more photons to the modules. Thus, more pairs of electron-holes will be produced which result in more current. In contrast, there are some factors that affect PV efficiency. The major factors are: temperature of solar cell, dust and humidity. Sun irradiation on solar cell can be blocked by dust. Also, photovoltaic cell efficiency will be decreased when temperature increases. In fact, Band gap of solar cell will shrink if temperature increases. Shrinkage of Band gap causes dropping of open circuit voltage.

4.3.2 Technological barriers

The technological fundamental barrier exit currently and – is expected to be overcome in the future due to technology development and research progress in the field:

One of the major barrier can be solar cell material for the efficiency enhancement and reduction of module area as Pandey et al. (2016) discussed (See section 4.3.1 for more information).

4.3.3 Energetic appraisal

With regard to energy resources, solar radiation to the earth surface is a theoretical potential which can be used as an index for comparing solar energy to other energy resources. Theoretical potential is the yearly radiation to the ground surface (KWh/year) considering physical parameters such as irradiation flux, cloudiness hours (Izadyar et al., 2016). The Sun's radiation (flux) in space is 1,368 W/m², while the available Sun's radiation on the surface of the earth is 600-1000 W/m² due to the atmospheric effects. However, surface of the earth, depend on the area, will receive an average of continuous flux between 100 and 300 W/m² due to day/night cycle and year (Seboldt, 2004). The sun power on the surface of the earth is around 1.4 x 10^5 TW, while only about 3.6 x 10^4 TW of it is usable (Hosenuzzaman et al., 2015). Figure 34, shows annual average solar irradiance.

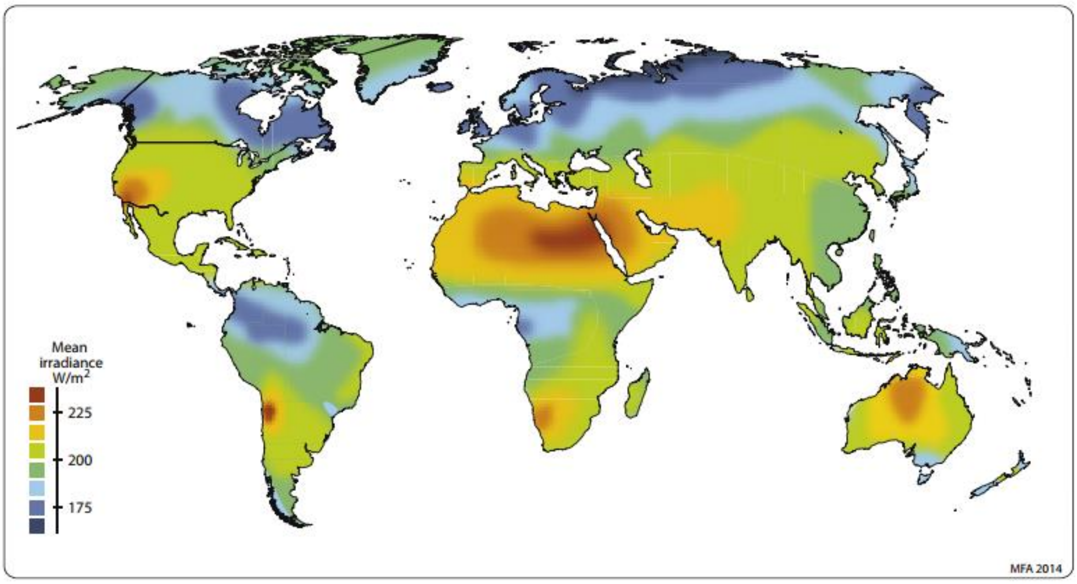

Figure 34: Map – Annual average solar irradiance (Ashby, 2016: 182)

Power generation system are considerably affected by Sunny and cloudy days (Hosenuzzaman et al., 2015).

- **PV plant production calculation**

According Fechner (2015), following formulas are used for calculation of production of PV power plant:

Production [kWh] = FLH [kWh/kW] x Power [kWp] (2)

Full Load Hours (FLH) [kWh/kW] = annual radiation x [kWh/m^2/a] x performance ratio (3)

The FLH is dependent on the annual radiation on the specified area and the PR[10].

According to Hosenuzzaman et al. (2015), PV based electricity is mostly produced by countries: Japan, Germany, UK, China, Spain and Italy. "*The total PV installation capacity is capable of producing 110 TWh/year electricity*" (Hosenuzzaman et al., 2015: 295).

4.3.4 Energetic barriers

Some of the energetic barriers exit currently and – is expected to be overcome in the future can be described as follows:

- Solar cell material and efficiency as discussed in 4.3.1.
- PV system are affected by day/night cycle and weather. Thus, PV system can provide baseload power only by using or being integrated into large storage systems such as batteries, pumped water storage and flywheels. It has to be taken into account that going to a storage system and coming back to use, causes energy loss in form of waste heat (Mankins, 2014).

4.3.5 Environmental appraisal

As already mentioned in 3.3.5, Life cycle analysis (LCA) can be generally used to assess all relevant system environmental impacts from cradle to grave as per ISO 14040/14044:2006. Environmental impacts are widely assessed by LCA. In this regard, LCA practitioners has been recently provided based on an issued guidance by IEA. For PV technology, until now, LCA had two major purposes as following: (Chatzisderis et al., 2016).

- To document and compare the environmental performances related to specific technology to other RE systems
- To guide scientific R&D.

[10] "*The term "performance ratio" refers to the relationship between actual yield and target yield. The performance ratio of a photovoltaic system is the quotient of alternating current (AC) yield and the nominal yield of the generator's direct current (DC). It indicates which portion of the generated current can actually be used. A photovoltaic system with a high Efficiency can achieve a performance ratio over 70 %. The performance ratio is also often called the Quality Factor (Q). A Solar Module based on crystalline cells can even reach a quality factor of 0.85 to 0.95 (performance ratio = 85 - 95 %)":* performance-ratio: http://www.solarserver.com/knowledge/lexicon/p/performance-ratio.html

Greenhouse Gas Emissions: In 2014, global electricity consumption was 21.000TWh **(**21 x 10^{12} kWh) per year. This amount is equal to amount of 2.4TW as an average continuous power consumption. Burning fossil fuel has a share of 80% of this level of electricity consumption – result in release of 10 billion tonnes of carbon emissions yearly (Ashby, 2016). In contrast, *"PV systems are defined as zero emissions or emissions-free energy system. In fact, PV systems have a negligible effect on greenhouse gas emissions. During PV system operations, There are zero release of CO_2, NO_x and SO_2 gases and it does not contribute to global warming*" (Hosenuzzaman et al., 2015: 292). Amount of 0.53 kg CO_2 emission can be saved by every produced kWh electricity via PV system when compared to the average emission rates released by natural gas and coal (Hosenuzzaman et al., 2015). (See table 11 and 12)

Table 11: Average Emission Rates (ibs/mwh)[11] (Hosenuzzaman et al., 2015: 292)

Source	Natural gas			Coal		
	CO_2	NO_X	SO_2	CO_2	NO_X	SO_2
EPA, eGRID 2000	1135	170	0.10	2249	6.00	13.00
ECONorthwest, eGRID 2006	1169	0.69	0.02	2164	3.50	10.30

Table 12: Emission reductions – replaced fuel (Kilotons/year) (Hosenuzzaman et al., 2015: 293)

Probability	Total PV capacity	Natural Gas			Coal			Total		
	Capacity(GW)	CO_2	NO_X	SO_2	CO_2	NO_X	SO_2	CO_2	NO_X	SO_2
2015 Minimum	5	3122	1.84	0.04	1927	3.11	9.17	5049	4.96	9.21
2015 maximum	10	7026	4.14	0.09	4336	7.01	20.63	11,362	11.15	20.72
2030 Minimum	70	42,938	25.34	0.55	26,495	42.85	126.11	69,434	68.19	126.66
2030 maximum	100	62,456	36.86	0.80	38,539	62.33	183.43	100,995	99.19	184.23

PV System Operation: As Kaltschmitt et al. (2007) mentioned, operation of Photovoltaic electricity generation is noiseless and PV system releases no toxic material. However, some typical environmental impact can occur due to solar cell manufacturing and PV system operation malfunction as following:

- Environmental impacts due to solar cell manufacturing:
  - Some mineral resources used for solar cell are *scarce (e.g. indium (In) for CIS and tellurium for CdTe solar cells)* which are available on earth with limited

[11] *"There are two sets of emission rates in use as follows: (i) EPA from eGRID 2000 database; and (ii) calculated by ECONorwest using the most accurate eGRID data available"* (Hosenuzzaman et al., 2015: 292)

quantities. Consuming of such resources must be taken into account (Kaltschmitt et al., 2007).

- Toxicity: Some Gaseous toxic substances may be produced during cell process (e.g. Hydrogen Selenide (H_2Se) related to Copper Indium Selenide (CIS) solar cell (Kaltschmitt et al., 2007). Thin film PV cells contains some toxic materials. Therefore, they can effect on the environmental (Izadyar et al., 2016).

- Raw material extraction needs mining operation which can harm miners. Moreover, mining machine causes air pollution (Tyagi et al., 2013).

Environmental impacts due to operation malfunction: Operational malfunctions of PV generators can impact on human and environment. Therefore, Power disconnection detection and auto shutoff shall be considered in system design. To meet the requirements, system shall be equipped with modern inverters and safeguarding equipment (Kaltschmitt et al., 2007).
Large solar farm causes visual impact (Ashby, 2016)

End of operation: Environmental impacts due to recycling is very dependent on solar module type and related components. For example, recycling of glass components is easy. In some cases pre-treatment and advance separation chemical process is required. With respect to recycling, studies shows that amorphous frameless modules are the best. They can be transferred to hollow glass recycling and no pre-treatment is required. Further assessment is needed for CdTe and CIS technologies with regard to precluding their heavy metals. Environmental effects, due to recycling, are expected to be reduced in future (Kaltschmitt et al., 2007).

4.3.6 Environmental barriers

Some environmental barriers exit currently and – is expected to be overcome in the future. For example, as Chatzisderis et al. (2016) discussed, *"a number of studies have thus warned against risk posed by global deployment of PV systems at the terawatt scale of installed capacity, e.g. the pressure on critical materials like rare earth metals from different solar cell technologies"* (Chatzisderis et al., 2016: 2). Critical materials are: silver, indium, gallium and tellurium. These materials use for manufacturing of some PV panels (Ashby, 2016)

4.3.7 Economic appraisal

As Kaltschmitt et al. (2007) mentioned, economic analysis of a typical PV power generation system refers to the following:

- **Investment costs:**

The following costs are to be considered during installation of PV power generation:

- Module and Inverter cost
- Frames, design and mounting cost
- Building permits cost
- Etc.

It is to be taken into account that plant size plays an important role in installation cost. Installation cost will decrease by increasing size of plant.

- **Operation costs:**

Annual costs of PV operation are basically depend on the plant size and type of installation. Operation cost is to be considered for maintenance and repair, servicing, module cleaning, insurance, etc.

- **Power production costs*:***

Power production cost can be calculated by use of annuity method based on the investment and operating costs.

As Weißensteiner (2014) mentioned, annuity is calculated by use of following formulas:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \qquad (4)$$

NPV: Net Present value (€)
T: Investment Horizon (Y)
T: Year-count
Ct: Cash flow in year t (€)
r: risk adjusted discount rate / WACC (weight average cost of capital)
C0: Initial investement (€)

Annuitiy:

$$a = NPV * \frac{r * (1+r)^T}{(1+r)^T - 1} \qquad (5)$$

a: annity
r: Internal rate of return (IRR)

As Hosenuzzaman et al. (2015) discussed, cost effectiveness is the most important challenge of producing energy via PV. In this regard, following parameters are studied by researchers for economic assessment:

- Net Present value (NPV): Positive NPV indicates profit
- Payback period (PBP): Number of years necessary for realizing total investment including Project and module payback.
- Internal Rate of Return (IRR): Discount rate for reducing the NPV of Investment to zero.

Climate change mitigation strategies made solar PV one of the most promising technology (Chatzisideris et al., 2016). Nowadays, investment on solar PV is increasing fast. *"New investments for PV solar system have increased by about 44% at around US$128 billion"* (Hosenuzzaman et al., 2015: 291). Also, in order to increase the use of renewable energy, different policies for financial support have been provided by different countries. Feed-in-Tariff and quota systems are used by most counties (Hosenuzzaman et al., 2015). As Trappey et al. (2016) mentioned, in 2013 the investment on solar power was US$ 113.7 – which 90% of this amount (US$ 102.3) was planned to increasing solar PV capacity worldwide. Furthermore, government policy for feed in tariff (FIT), in development countries helps to install more PV systems. Increasing the global installed PV results in PV price decreasing according to learning curve effect[12]. *"For the countries participating in the IEA-PVPS, the total installation capacity has been found to be increased from 103 MW in 1992 to 63,611 MW in the year 2011"* (Pandey et al., 2016: 861). Nevertheless, Full levelised cost of electricity generated (LCOE) shows that in less sunny location, cost of electricity generated by solar PV is not cheap. Cost of storage, when it is needed, should also be considered. Levelised cost of electricity generated calculates with considering the parameters: Module margin, BOS of system component costs Installation costs, O&M costs, System Lifetime, Module degradation rate, Discount / finance rate, Irradiation level (Gambihir et al., 2016).

4.3.8 Economic barriers

As Hosenuzzaman et al. (2015) mentioned, cost of electricity generated by conventional system is lower than that generated by PV based system. Therefore, production cost must be reduced aiming to make this technology widely acceptable. In this regards cost of Module manufacturing, cell efficiency and balance of system (BOS) are to be considered.

[12] "*The concept of the learning curve was first introduced by Wright. By observing the production processes of aircraft manufacture, Wright (1936) showed that when production quantity doubles, the cost of producing a plane decreases at a constant rate*" (Trappey et al., 2016: 1710).

As Gambihir et al. (2016) mentioned, assessment of PV power generation shows that further cost reduction is necessary to be cost-competitive with other conventional electricity generation technologies.

4.4 Future perspective

4.4.1 World energy consumption

In 21st century, energy crisis is one of the major topics. Energy demand is continuously increasing. As figure 35 shows, the world total energy consumption is projected to increase by 44% from 2006 to 2030 (Jibran & Mudassar, 2015; Pandey et al., 2016).

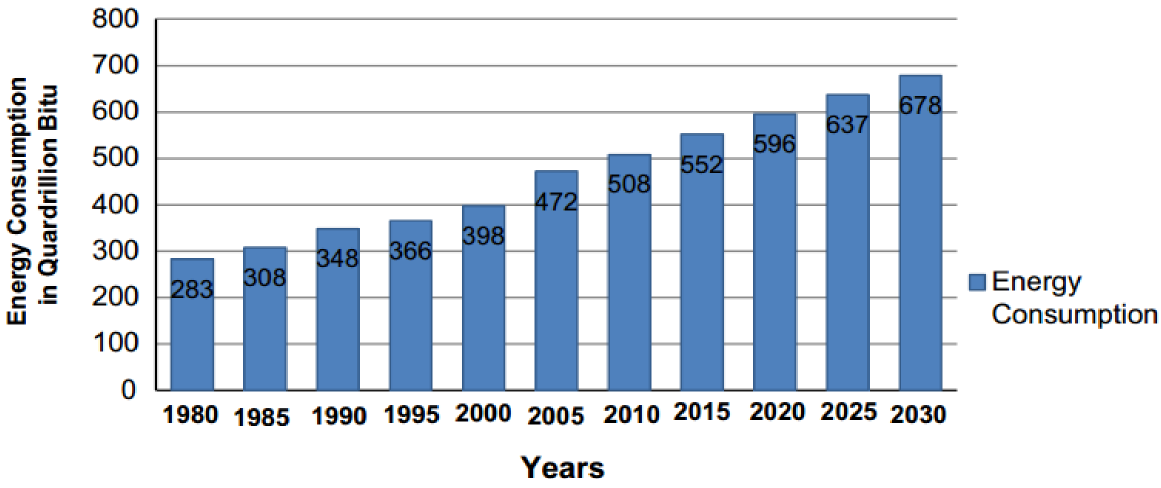

Figure 35: Projected World Energy Consumption (Jibran & Mudassar, 2016: 415)

At present, fossil fuels has a very large share in global energy mix. However, burning fossil fuels have negative environmental impacts (Jibran & Mudassar, 2016). Currently (2014), Solar PV has only about 4% share of total electricity generation and it is expected to increase to 20% until 2023 (Ashby, 2016).

Table 13: Forecast – Energy/CO_2 emission (Mankins, 2014: 21)

		2012	2030-40	2060-70	2090-2100
Global Population	High	~ 7 billion	~ 9 billion	~ 11.5+ billion	~ 12.5+ billion
	Medium	~ 7 billion	~ 8.5 billion	~ 9+ billion	~ 8.5+ billion
	Low	~ 7 billion	~ 7.5 billion	~ 7+ billion	~ 5.5+ billion
Current / Projected Global Annual Energy Consumption[4]		~120,000 Billion kWh	~220,000 Billion kWh	~400,000 Billion kWh	~480,000 Billion kWh
Low Renewable Energy Case	Renewable Energy: Low Share Case [5,6]	~10%	~10%	~10%	~10%
	IPCC Projection: High CO_2 Emissions Case [7,8]	~31 bn MT/year	~55 bn MT /year	~100 bn MT /year	~125 bn MT /year
High Renewable Energy Case	Renewable Energy: High Share Case	~10%	~50%	~70%	~90%
	IPCC Projection: Low CO_2 Emissions Case	~31 bn MT /year	~28 bn MT /year	~22 bn MT /year	~15 bn MT /year

As Mankins (2014) discussed, world's growing population, global economic growth and higher quality of life resulted in increasing energy primary demand for heating, cooling, transportation and electrical power generation. It is estimated that world population will be around 12 billion in 2100. Table 13 shows that, global energy consumption will be incresed 4 time in 2100 compared to 2012. Today, world energy consumption is about 120,000 billion kWh per year. Fossil fuels have a 85% share of this amount – including coal with about 29%, oil with about 33% and natrul gas with about 23%. This results in a significant amount of greenhouse gas emissions and global warming. Moreover, fossil fuel is limited. At present, Annual energy consumption per capita is 60,000 kWh/person-year is in US, Canada, Japan and European countries. This includes all types of energy. Global energy consumption is around 17,000 kWh/person-year and is estimated to increase to 38,000 kWh/person-year by 2100. At present (2013) – by the current level of global energy consumtion, it is expected that oil supply will be depleted by 40-50 years, coal by 100 years and natrul gas by 100-200 years. With respect to CO_2 emmissions, many scenarios have been developed and significant efforts have been made by different organizations such as the International Panel on Climate change (IPCC). The analytical scenarios shows the importance of using renewable and sustainable energy sources (Mankins, 2014).

4.4.2 PV global installed capacity

As Chatzisideris et al. (2016) discussed, according to Energy Agency's IEA BLUE Map scenario, large scale of low carbon energy technologies is essential to cover electricity demand in 2050. Therefore, it is suggested to increase the combined share of solar, wind and hydro power in total electricity generation to 39% in 2050 compared to 16.5% in 2010. PV global installed capacity is projected to increase to 1721 GW by 2030 and 4674 GW by 2050 compared to 135 GW in 2013. As Chatzisideris et al. (2016) mentioned, Climate change mitigation strategies made solar PV one of the most promising technology.

Recently, some countries plan to cover their energy demands by use of RE electricity, mostly solar and wind (e.g. Denmark's Plan: 100% RE; Germany aims to cover 80% of power demand via RE by 2050). Several other countries are discussing about increasing share of RE electricity in their energy demand (Lund et al., 2015).

PV based electricity is mostly produced in countries: *Japan*, *Germany*, *UK*, *China*, *Spain and Italy*. Europa with 55% of share has the largest share in the PV market. The following capacities are estimated for the countries: "*Germany 7.6 GW, China 5 GW, Italy 3.4 GW, USA 3.3 GW and Japan 2GW* " (Hosenuzzaman et al., 2015: 291).

4.4.3 Technological perspective

- **PV technology:**

One of the important parameter to put the solar cell in the market is cell efficiency Thin film seems to be a promising technology in the future. Low price due to advances in technology, is also expected. Current technology development make it possible to reduce price particularly for large area module production (Hosenuzzaman et al., 2015). Organic cells are favorable to use due to low manufacturing cost, low weight, transparency property, flexibility and environmental-friendly. However, organic cells reaches still very low efficiency compared to other types. Approximately 8% efficiency has been reported for organic cells (Pandey et al., 2015; Gambhir et al., 2016).

Figure 36: Organic Solar Cell (Fechner, 2015: Script MSc Program)

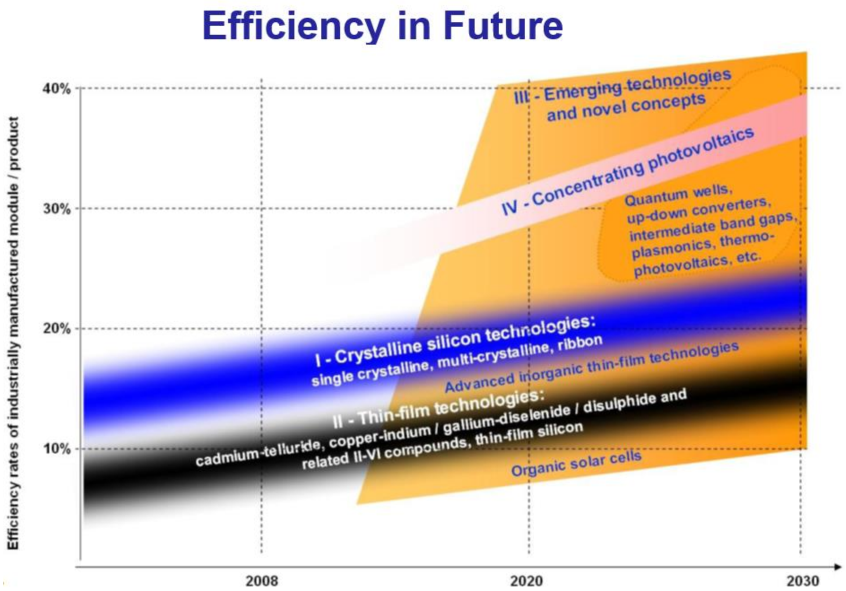

Figure 37: Solar cell efficiency in Future (Fechner, 2015: Script MSc Program)

- **Energy system flexibility**

As Lund et al. (2015) mentioned, Renewable Energy sources are projected to have significant share of global electricty by 2050 according to many studies and scenarios. Therfore, large amount of variable renewable electricity (VRE) such as wind and solar power will be integrated into the existing power system. Thus, it is necessary to make balance between supply and demand which means flexibility in energy system. With respect to electricity system, flexibilty is related to grid frequency and voltage control, delivery uncertainly and variability and power ramping rates. For example, in the electric grid, power supply and demand must balance at all time. Flexibility requirement, in conventional power system, is achieved via different types of power plants. Flexibilty improvement is required when share of VRE increases (e.g. for distribution and transmission system network). That means, new kind of flexibilty measures are required. Therefore, energy storage technologies have become of interest. Energy storage ensures system stability. Morevere, Energy storage is required when large amount of RE power is produced but transmission capacity is limitted. If grid is not ready, storage system stores RE power production and storage will be discharged as soon as grid is ready. The other solution can be increasing of transmission capacity. Technologies such as batteries, compressed air (CAES), hydrogen and pumped hydro power energy storage (PHES) are suitable for large amount of energy. Also, Smart grid (SG) improves system flexibility. Use of SG is an intelligent way to connect energy producers, consumer and network companies to each other. Smart grid increases power supply reliability. Furthermore, SG makes it possible to integrate all energy producers to the grid and participate to the grid optimization which results in carbon emission reduction as well as major saving. Super-smart grid would be future technology development of Smart grid. Super-smart grid would use advantages of both supergrid and smartgrid.

4.4.4 Energetic perspective

As already mentioned in 4.4.2, According to IEA BLUE Map scenario, a technology roadmap for solar energy has been planned by IEA in 2014. According to the plan, it is projected that PV global installation capacity increases to *1721 GW by 2030 and 4674 GW by 2050,* compared to amount of 135 GW in 2013 (Chatzisideris et al., 2016). According to Ashby (2016), at present (2014), PV has only about 4% share of total electricity generation.
However, Installation of solar power is growing fast (40% per year). Furthermore, increasing efficiency of solar PV system causes of cost PV system reduction. Moreover, solar PV technology is able to guarantee reliable power for minimum 25 years. Due to such factors, it is estimated that solar PV contributes about 20% of total world electricity generation by 2023 (Ashby, 2016).

4.4.5 Environmental perspective

As already mentioned in section 4.4.2, with respect to climate change mitigation strategies, carbon reduction is a target of many countries. For example, Europa has a target of 20% and 80% carbon reduction by 2020 and 2050 respectively (Ashby, 2016).
Table 14 shows that, *"Use of PV systems can reduce 69 -100 million tons of CO_2, 68,000 – 99,000 t of NO_x, and 126,000 -184,000 t of SO_2 by 2030"* (Hosenuzzaman et al., 2015: 292)

Table 14: PV-Emission reductions – replaced fuel (Kilo t/year) (Hosenuzzaman et al., 2015: 293)

Probability	Total PV capacity	Natural Gas			Coal			Total		
	Capacity(GW)	CO_2	NO_X	SO_2	CO_2	NO_X	SO_2	CO_2	NO_X	SO_2
2015 Minimum	5	3122	1.84	0.04	1927	3.11	9.17	5049	4.96	9.21
2015 maximum	10	7026	4.14	0.09	4336	7.01	20.63	11,362	11.15	20.72
2030 Minimum	70	42,938	25.34	0.55	26,495	42.85	126.11	69,434	68.19	126.66
2030 maximum	100	62,456	36.86	0.80	38,539	62.33	183.43	100,995	99.19	184.23

4.4.6 Economic perspective

As previously mentioned, investment on solar PV is increasing fast. Recently investments have been increased by around 44% about US$128 billion (Hosenuzzaman et al., 2015).

Climate change mitigation strategies made solar PV one of the most promising technology (Chatzisideris et al., 2016). However, as Hosenuzzaman et al. (2015) mentioned, cost of electricity generated by conventional system is lower than one by PV based system. Therefore, production cost must be reduced.

As Gambihir et al. (2016), discussed, increasing the installed PV worldwide results in decreasing of PV price according to learning curve effect. However, further cost reduction is necessary to be cost-competitive with other conventional electricity generation technologies. In future, electricity price, can be reduced through use of silicon module which is estimated to be under US$1/Wp by 2020 or 2030 compared to previous decade. Other materials such as CdTe are competitors to share in the market around this price level. Assessment of organic photovoltaic (OPV) technology shows that OPV technology can provide cheap solar electricity due to current progress in module efficiency, life time and low cost mass production. However, future of OPV module cost is very depend to future material and cost of manufacturing. According to experts, with focusing on levelised costs in 2030, electricity cost around $0.10 is expected for PV generated electricity.

Also, as Lund et al. (2015) mentioned, Variable Renewable Energy (VRE) production will also affect the electricity markets. On the short-run, the electricity price on the wholesale spot market will be reduced due to VRE production fed to the market (e.g. wind and solar). For example in Germany, adding 1 GWh of VRE power to the grid results in lowering the spot market price of electricity by $1.4-$1.7/MWh. VRE are mostly supported by FIT. That means, VRE have been fed to the market. On long-run, increasing RE power results in decreasing demand for base load power plants and increasing demand for peak load. Therefore, net load fluctuation will be increased which causes price instability accordingly. *"The cost of RE and wholesale prices will also influence on investment, expansion and retiring decisions of transmission and generation in long run, making the average effect of RE on wholesale prices less clear on short term"* (Lund et al., 2015: 799).

Solar PV is projected to share about 20% of total world electricity generation by 2023 (Ashby, 2016).

PV based electricity is mostly produced in countries: Japan, Germany, UK, China, Spain and Italy. Europa with a 55% of share has the largest share in the PV market. (Hosenuzzaman et al., 2015).

5 SUMMARISED COMPARISON of SBSP versus EBSP

This part of the thesis focuses on the comparison between SBSP and EBSP, in order to give an overview of advantages and disadvantages of both systems, considering the current status and the future perspective.

As previously mentioned, according to Mankins (2014), sun energy in space near to the earth is significantly greater than at the surface of the Earth. Sunlight intensity in space is around 1,368 watts/m^2. By comparison, sun intensity is about 1,000 watts/m^2 on a clear day at noon at the surface of the earth and close to the equator. However, Energy loss occurs due to the day/night cycle (about 60%), weather - light clouds and heavy clouds (20% and 70% - 80% respectively). That means, availability of sun energy in space is greater than the availability of sun energy at the best area on earth. Available energy in GEO is 10 times greater than on earth. Figure 38 shows hour-by hour average difference in solar energy in June at GEO vs. Earth at middle latitude in North America. Therefore, due to the mentioned loss factors, EBSP is not able to produce power - 24 hours a day - continuously, while power plants such as nuclear and coal fired can provide electricity continuously independent of the weather and the season. Thus, the biggest challenge for EBSP is when it contributes to market demand – *"baseload"*. EBSP can provide baseload power only by using or being integrated into large storage systems such as batteries, pumped water storage and flywheels. It has to be taken into account that going to a storage system and coming back to use, causes energy loss in form of waste heat. Furthermore, a very large solar array is required to providing enough power during day. By comparison, energy in space is more readily availabe.

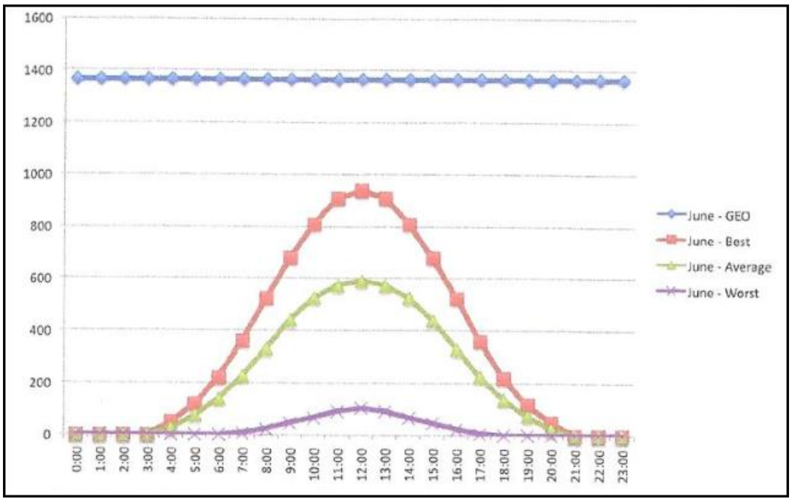

Figure 38: Solar Energy in GEO vs. Earth – June North America (Mankins, 2014: 6)

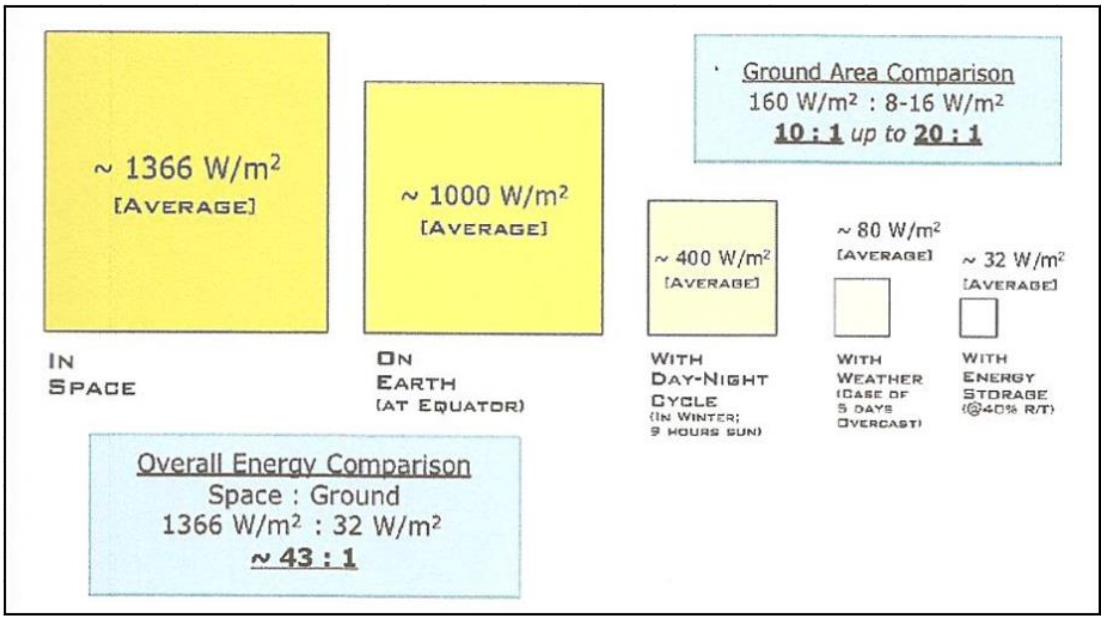

Figure 39: Solar array in Space vs. Earth for Baseload power (Mankins, 2014: 7)

As figure 39 shows, as an example, in order to provide baseload power an average area of solar power on the earth has to be 40 times larger than one required in space. Also, on the ground a larger area is required to deliver the given energy amount (10 - 20 times greater than in space). The comparison shows that, energy intensity can be varied as 40- to-1 for baseload power (Space vs. Earth). However, EBSP is very important for the energy future of the world. Although power from space seems to be potential sustainable energy in future, it is not yet realized. There are still critical technical challenges to be overcome.

Table 15: PROs and CONs – Comparison summary of SBSP vs. EBSP – Part 1 (own table)

Aspect	Current Status		Future Perspective	
	EBSP	SBSP	EBSP	SBSP
Technological	PROs (+) • Photovoltaic system has simple design • Easy to operate & maintain CONs (-) • PV efficiency is still low • Module area is still large • PV system performance depend on whether and location • PV performance loss due to weak radiation, thermal loss, etc.	PROs (+) • Technology development due to Space Solar PV industry CONs (-) • System design concept is still complex and needs more R&D • Low maturity of key technologies • System material, scale and mass are still a concern • Solar cell efficiency is low • Space access is difficult • System installation & maintenance is difficult • Need of highly qualified personnel	PROs (+) • Technology development due to Solar PV industry • Cell efficiency enhancement in progress • Low weight cell in progress, e.g. organic material (OPV) • Cell area reduction in progress • Improvement of energy system flexibility in pogress i.e. integration of Variable Renewable Energy (VRE) production into the existing power system (e.g. energy storage system; smart grid) CONs (-)	PROs (+) • Technology development due to Space Solar PV industry • Simpler design development in progress • System optimization of key components (such as system mass, system efficiency and energy distribution) in progress • Solar cell efficiency enhansment in progress • Reusable launch in development CONs (-)
Energetic	PROs (+) • The total global PV installation capacity is capable of producing 110 TWh/year electricity • Fast growing (Worldwide arround 23.5 GW in 2010 and also growing at an annual rate of 35-40%). CONs (-) • Low Sunlight intensity at surface of the Earth (600 - 1000 W/m²) due to atospheric effect • Averge **600 - 300 W/m²** due to day/night cycle & year. • Loss of PV performance due to weak radiation, thermal loss, etc. • PV system can only provide base load power if it is integrated in large-scale energy storage system such as batteries or pumped water storage • Low share in global electricity generation (4%)	PROs (+) • High Sunlight intensity (**1.368 W/m²**) • Available solar energy at GEO is 10 time greater than the best average available at most locations on earth • Sun energy is always availabe and does not depend on day/night cycle & year - thus SBSP can provide base load power • No PV performance loss due to weak radiation, etc. CONs (-) • Not yet operational	PROs (+) • Increase of PV global installation capacity to 1721 GW by 2030 and 4674 GW by 2050 is projected (IEA BLUE Map) • 20% share of total world electricity generation by 2023 is projected CONs (-) • PV system can only provide base load power if it is integrated with large-scale energy storage system such as batteries or pumped water storage	PROs (+) • Possibility of high potential clean & sustainable energy - **2 GW** power by 2050 is planned by the US; **1 GW** power by 2030 is plannd by Japan • Very high amount of energy availability on earth, independent of location, that could provide baseload power CONs (-)

Table 16: PROs and CONs – Comparison summary of SBSP vs. EBSP – Part 2 (own table)

Aspect	Current Status		Future Perspective	
	EBSP	SBSP	EBSP	SBSP
Environmental	PROs (+) • Operation of PV electricity generation is noiseless • PV system releases no toxic material • No release of CO2, NOx and SO2 during PV system operation and It does not contribute to global warming • 0.53 kg CO2 emission can be saved by every produced kWh electricity via PV system when compared to average emission rates released by natral gas and coal CONs (-) • Use of critical materials for some PV manufacturing: Indium,Galium, Silver, Tellurium • Gaseous toxic substances during cell process (e.g: H2Se related to Copper Indium) • Solar farms require a large area (visual impact)	PROs (+) • Limited effect on global warming (Analysis of SSPS 1.5 GW showed less than 0.000001 °C rise when delivering power to earth) • SSPS releases low carbon dioxide into the environment (Analysis of SSPS 1 GW will release 12.22g of CO2 when producing 1kWh) CONs (-) • Space debris • Launch causes some pollution (e.g. Pollution which comes back to earth during accelerator stage after fuel exhaustion) • Launch local impact: hydrochloric acid and alumina concentrations mostly on the Launch area less than 2.3 km • WPT environmental impacts (e.g. interference with other system) • Risk of nuclear critically emergencies	PROs (+) • Use of PV systems can reduce by 69 -100 million tons of CO2, by 68,000 – 99,000 t of NOx, and by 126,000 -184,000 t of SO2 by 2030 (replacing nstural gas and coal) CONs (-)	PROs (+) • Overcoming environmental crisis is expected • Minimal environmental impact is expected of WPT CONs (-)
Economic	PROs (+) • FIT support, higher grid electricity prices, lower installation costs makes PV attractive for investors CONs (-) • Highly efficient cell is expensive • Solar PV electricity is more expensive than electricity from national power grid • Higher cost related to energy storage system due to increasing share of PV in grid • Longer payback time in case of reduction of FIT	CONs (-) • High investment risk because research and development is needed • High cost due to system material, mass and transportation from earth to space and in space via launch • High cost of crew training and salaries • High cost of system assembly, integration, management, operation and maintenance • Energy price is not yet competitive with current market price	PROs (+) • Higher efficiency through more installed PV worldwide and PV price decreasing due to learning curve effect • OPV technology can provide cheap solar electricity due to progress in module efficiency CONs (-) • Higher cost related to energy storage system due to increasing share of PV in grid • Longer payback time in case of reduction of FIT	PROs (+) • SBSP would be able to compete with current market prices because of expected cost reduction per kWp over time CONs (-) • High investment risk • High development cost • Need for long term major investors

6 CONCLUSIONS

The research questions have been addressed in detail in the previous chapters (see references below). This chapter highlights the most important lessons that can be learned from the detailed analysis. I then conclude with a look to the future of SBSP and open questions, to answer the final research question: "What are open questions with regard to the future use of SBSP?"

- What is the current status of Space Based Solar Power (SBSP) and Earth Based Solar Power (EBSP)? (See 3.3 & 4.3)
- What are the future perspectives of SBSP and EBSP? (See 3.4 & 4.4)
- To what extent is SBSP feasible and safe and what are the key barriers to SBSP? (See 3.3 & 3.4)
- What are the advantages and disadvantages of SBSP in comparison to EBSP? (See 5)
- Will SBSP be able to solve the problem energy and environmental crisis on our planet? (See 3.3, 3.4 and 6.2)

6.1 Main lessons

According to Mankins (2014), world population will probably increase from 7 billion in 2012 to 12 billion by 2100. In 2012, world energy consumption was about 120,000 billion kWh per year (2012) and energy demand is continuously increasing. The huge energy consumption has made the world dependent on fossil fuels and nuclear power.

Fossil fuels have a 85% share of this amount – including coal with around 29%, oil with about 33% and natural gas with about 23% – which results in a significant amount of greenhouse gas emissions and global warming and finally an energy and environmental crisis.

Since energy demand, until now, is not dominated by Green Technologies such as wind, solar or hydro power, CO2 emission is still considerable. Indeed, the current Green Technologies are not able to cover a high amount of continuous baseload power which will be required in future. On the other hand, only renewable energy sources are able to prevent the environmental crisis.

Many scenarios have been developed with regard to low carbon energy technologies. According to all scenarios, solar PV technology seems to play a key role in reducing GHG by 2050. According to Chatzisideris et al. (2016), GHG emission which is released by power generation shall be reduced to 76% by 2050, compared to 2007. To meet this requirement, it is suggested to increase the combined share of solar, wind and hydro power in total energy generation by a 39% share in 2050. Climate change mitigation strategies made solar PV one of the most promising technologies.

Based on the IEA BLUE MAP scenarios, as planned in 2014, PV global installation capacity will be 1721 GW by 2030 and 4674 GW by 2050. Also, the PV generated electricity, at present (2014), is 4% of total world electricity generation. It is projected that PV will contribute about 20% to total world electricity generation by 2023 (Ashby, 2016). Most scenarios show that solar (earth based) PV technology is able to guarantee reliable power in future. Furthermore, *"Use of PV systems can reduce 69 -100 million tons of* CO_2*, 68,000 – 99,000 t of* NO_x*, and 126,000 -184,000 t of* SO_2 *by 2030"* (Hosenuzzaman et al., 2015: 295).

Overall, PV technology development is in progress and EBSP currently makes only a small contribution to meeting the high world energy demand. However, according to Mankins (2014), SBSP would have a much more significant potential to provide possible clean and sustainable energy in the future, if it is realized.

6.2 The future of SBSP and open questions

According to the researched published papers and data, SBSP has many advantages and can be sustainable energy in the future. Realizing the SBSP vision would provide the opportunity to use high potential sun energy which is clean and safe. However, Space Based Solar Power is still confronted with many challenges and major barriers have to be overcome to approach the goal (also see barrier chapters). The following section of the paper gives an overview of SBSP challenges with respect to political, technical, economic challenges as well as challenges related to public and business awareness. (See Figure 40)

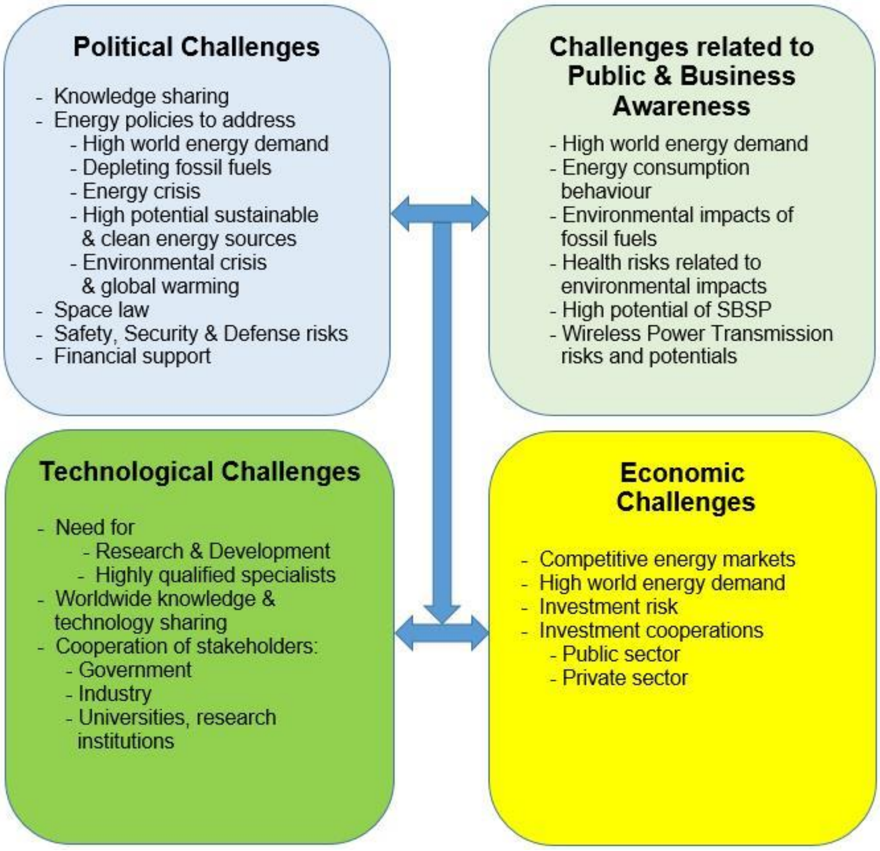

Figure 40: Overview – SBSP Challanges (own graphic)

- **Political Challenges:** Future development of Space Base Solar Power depends not only on technical and economic challenges but also on political challenges. At the political level, knowledge sharing on policies between countries and other stakeholders would be needed. An example of such a cooperation are the efforts of the Committee on the Peaceful Uses of Outer Space (COPUOS), established by the UN. Further development of space laws and regulations need more research.

Also, political support is essential for SBSP development. This is especially related to financing. Furthermore, political stakeholders have a major role in promoting public awareness and national and international policy support can significantly help SBSP development.

- **Public & business awareness:** This part is mainly related to promoting public and business motivation to use renewable energy sources and to change consumer behaviour. Today, there is enough knowledge and information to make people conscious and aware of the need for using clean and sustainable energy sources. However, without business awareness there will be no success. Indeed, in many cases businesses design many things we need for our daily life such as buildings, automobiles, computers, etc. In other word, our life style is very dependent on business decisions. Therefore, it is necessary to promote public & business awareness of green energy and particularly of high potential solar energy which is sustainable and clean and could be equally available to all nations. Many people are not well aware of the environmental crisis due to the use of fossil fuels and the dangers of nuclear power. With regard to the energy crisis and the high global energy demand, it is very important to motivate consumers to change their behaviour. With respect to safety concerns for humans and the environment, more education is still required, e.g. on wireless power transmission electromagnetic interference. Another example is that many people may not know that radio waves can also be used for carrying energy. For them usage of radio waves means communication (radio, TV, phone).

- **Technological challenges:** Although promising technology makes SBSP viable, more technology improvements are still needed to realize it. Researchers are still concerned about system optimization of key components such as system mass, system efficiency and energy distribution, which needs further works. Therefore, more research and development is still needed. In this regard, sharing knowledge internationally would facilitate more progress. Also, cooperation between universities, research institutions, industries and government seems to be a key to success with regard to efficient research and development of SBSP. As mentioned before, political stakeholders play a role in its facilitation.

- **Economic challenges:** In the future SBSP should be able to compete with other energy sources at the energy market. Currently, however, it cannot compete because energy from sources such as coal, oil, and nuclear material are relatively cheaper and still more easily accessible. The major key factors for the business case of SBSP are return on investment and risk. With regard to SBSP there is still a high investment risk because the technology is at research level and in development, which requires high long term investment. High risk investors expect high returns on investment (interest). For investors, who need a market perspective, it is very important to know the amount of money they will have to invest, the amount they will receive and the investment period, to calculate the rate of return. Potential efficiency gains and increased effectiveness as a result of the learning curve have to be considered. Theoretically, a cost reduction per kWp over time is to be expected due to producing a very high amount of energy by SBSP. One of the advantages for investors in this field would be the ultimately much cheaper energy production. The investment risk could be reduced by joining public and private sector co-funding in this business field. With respect to world energy demand, high amounts of SBSP production would help to cover global high energy demand. According to researchers, SBSP is not yet economically viable due to system cost as well as cost of transportation to space. SBSP investment potential will grow as technical challenges are overcome.

Today, we face serious problems related to energy and environmental crisis, which must not be ignored. In recent time, it seems that finding possible solutions for these problems has become a great challenge, especially for highly industrialized countries. In this regard, many scenarios have been developed and significant efforts have been made by different organizations such as the International Panel on Climate change (IPCC). There are also significant assessments in progress with the objective to stop global warming, but they are still far from a possible solution. According to experts, Space Based Solar Power would be a possible solution and could be a key driver for clean and sustainable energy in future. However, if we look to the history of research on SBSP, which has started due to the oil crisis in the 1970s, progress seems still quite slow. Then, my open questions with regard to the future of SBSP are: Why does the realization of SBSP not have a higher priority? What exactly does SBSP need to be successfully realized? More national and international policy support for efficient research and development may be needed, as well as investment support. Raising public & business awareness may be the key for success.

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