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HELIODROMUS: RENEWABLE ENERGY FROM SPACE

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Climate change and the related running out of fossil fuel reserves drive the development of renewable energy sources. To contribute to a solution of these problems, we present the results of a BSc student design synthesis exercise project on Space Based Solar Power (SBSP). A SBSP system generates power in space using solar cells concentrator systems and wireless power transmittance to Earth. Main advantages compared to terrestrial solar conversion systems are a higher surface power density and continuous power supply.

The project includes an analysis of the current and future electricity market, its technical performance, the conceptual design of a SBSP system, the economical aspects and sustainability. The SBPS top level requirements are an operational lifetime greater than 10 years, an end of life effective power output on Earth exceeding 1 GW, a launch before 2025 and being cost-competitive with terrestrial energy sources. Besides these top level requirements, numerous derived requirements are established on sustainability, safety and (subsystem) design. The SBPS concept, termed Heliodromus, resulted from a broad study starting with three existing concepts. A systems engineering trade-off resulted in a new constellation concept: Ten satellites orbiting in Low-Earth Orbit and two satellites orbiting in geostationary Earth orbit each having five mirrors.

The performance of Heliodromus was evaluated by the following criterea: overall efficiency, technical readiness levels, energy payback time and total cost. The major losses occur during the initial energy conversion, with only 15% efficiency, by the photovoltaic thin films. Heliodromus is 5 to 10 times more expensive compared to existing Earth based solar farms, both photovoltaic and solar dynamic. The energy payback time is 6 years compared to 3 years for terrestrial solutions. The worst case estimate of Heliodromus' efficiency is 2% which is not sufficient to compete with Earth-based solar systems. However, due to the ongoing rapid developments, an overall efficiency of 10% efficiency is credible in the present decade.

The (worst case) electricity cost is 1 \$ per kWh compared to 0.1 \$ per kWh for a (2010) terrestrial power plant. The cost of Heliodromus is around \$98 billion and at this stage it is not price-competitive with fossil or Earth-based renewable energy sources. The required assembly in orbit was never done on the scale required for Heliodromus, therefore it opens totally new fields of research and development. The total efficiency was defined worst case but the improvement of electronic components efficiency will continue. Therefore a factor 5 improvement in the near future is probable, getting Heliodromus closer to becoming market viable.

I. INTRODUCTION

Renewable energy sources are becoming more and more important as fossil fuel reserves are running out and become too expensive. Space solar power is in principle inexhaustible and delivers a clean form of energy [1]. This creates a potential for harvesting renewable energy from space by Space Based Solar Power Systems (SBSPS). Its principle [2] is shown in Fig-1 for a single SBPS spacecraft in a geostationary (GEO) orbit. The collector and antenna share a common axis parallel to the Earth. The antenna constantly faces the Earth whilst the collector (by rotation) normal follows the sun. The problems of power loss during transmission as well as the expense and difficulty of assembling large arrays of solar collectors in space have been intensively studied the last three decades [3,4,5]. The critical questions are about a 5000 GW system of 1000 plants worldwide [2].



Fig-1: Principle of a SBSP [2]

The working principle [2] of a SBSPS, shown in Fig-1, is the generation of power in space using solar energy conversion and subsequently transmitting this power to the Earth by means of wireless power transmission. The main advantages of a space system compared to terrestrial solar conversion systems are a higher surface power density (due to a higher sunlight intensity outside the atmosphere), and a continuous power supply (no day and night cycle).

A number of studies [3,4,5] was performed both in the US (SERT) and by ESA. Recently EADS Astrium [6] announced to boost their development effort to get a very high efficiency of conversion of the infrared laser beam light into electricity and announced that a demonstration mission should be possible in the present decade. Meanwhile Japan (JAXA) announced [7] it is planning to put a small demonstration solar collecting satellite in orbit by 2015.

At the TU Delft faculty Aerospace Engineering a student Design Synthesis Exercise (DSE) BSc project

[8,9] was dedicated in 2009 and 2010 to the design of a SBSPS. These kind of projects are part of the compulsory educational program to train students in systems engineering, project management and teamwork. Creativity and out-of-the-box thinking are key characteristics of the DSE. The writer of this article was the principle tutor and initiator of a 2009 DSE assignment with title and mission need statement:

"Design of a 'green' spacecraft series to supply renewable solar energy directly to Earth to be launched before 2025."

The project objective statement was defined somewhat different:

"Perform a market and technology feasibility study and make a conceptual design for a SBSP harvesting platform by 10 students in 10 weeks."

The project included an analysis of the current and future electricity market, a conceptual design of a SBSP system, an analysis on its technical performance, economical aspects and sustainability, and a comparison to Earth based solar farms. The SBSPS design result of this project named '*Heliodromus*', is described in this article. Keywords of the study are: Renewable energy, solar concentrators, energy conversion, solar cells, heat engines, GHz energy downlink, microwaves, laser beams, transmitter, system trade-offs, end-to-endperformance, market viability.

II. SBSP SYSTEM REQUIREMENTS

The mission need statement [8,9] gives rise to the following SBSPS mission requirements:

- Operational lifetime at least 10 years.
- 1 GW effective power output on Earth at End- Of-Life (EOL).
- Launch before 2025.
- Sustainable design.
- Cost-competitive with terrestrial energy sources.

Additional requirements were derived systematically during the design process. Besides these top level requirements, numerous other requirements are defined. These requirements state the criteria on sustainability, safety and (subsystem) design. A detailed treatment of the design is not within the scope of this article. Its contents confines towards the System Engineering approach, main outcome of the study and its follow-up in the DSE 2010.

III. CONCEPT STUDY

For the SBSPS trade-off start, three different existing concepts were considered. In Table-1 the specifications (SBSP characteristics) of these concepts are given.

III.I LEO concept

The Low Earth Orbit (LEO) concept, up to 1,500 kilometers altitude, consists of a constellation of satellites rotating the earth. For the collection of solar energy photovoltaic cells are used. A laser system was chosen for the transmission on basis of arguments from [10-15]. The stabilization of the system has to be performed actively, since the lasers rotate. An advantage of this concept is that the lasers can be transmitted to existing terrestrial photovoltaic farms, reducing cost.

Design Option	LEO	GEO	Mirror
Collection [space]	Plane wings	Plane wings	Parabolic / Spheric
Conversion [space]	PV	PV	None
Orbit height	1000 [km]	36000 [km]	36000 [km]
ADCS stabilization	Active	Active	Active
Contact time	Low	High	High
# of satellites	Multiple (± 50)	1	1
# of ground stations	Multiple (± 50)	1	1
Ground station type	Existing farms	Custom rectenna	Existing farms
Weather attenuation	High	Low	High

Table-1: The three SBSPS concept specifications.

Secondly, lasers are smaller, safer and lighter than microwave antennas. Moreover, the orbit can be chosen to deliver energy to Earth to serve during energy peak moments in the morning and evening. A major drawback of the LEO concept is the large amount of ground stations and satellites required to provide energy continuously, as the LEO satellites have a short contact time with a ground station.

III.II GEO concept

The GEO concept consists of a single GEO satellite, which is coupled to its own ground station. The system can easily be scaled with other GEO satellites and ground stations. For collection of solar energy photovoltaic (PV) cells are used in combination with solar concentrators, increasing the solar intensity. A microwave system is used for the transmission. The satellite stabilization has to be performed actively, since the PV cells have to rotate to the Sun. Advantages of the GEO concept are that the system is stationary above ground and microwaves are barely influenced by clouds. A disadvantage is that a large amount of mass and volume has to be launched to GEO height, which requires many launch vehicles, increasing the overall cost.

III.III Mirror concept

The space mirror concept consists of a single satellite in GEO and a corresponding ground station on Earth. The satellite is a mirror reflecting the solar radiation towards the ground station without converting it to other forms of energy. The concept excels in simplicity in the absence of a collection system, transmitting devices and cabling. As a result the complexity of the system and values for the mass and volume can be made significantly lower than for other design concepts. Just as the LEO concept, the mirror concept can make use of already existing photovoltaic farms, even more efficiently. A major drawback of the mirror concept is that it requires 'Soller slits' to create parallel solar beams for decreasing the spot on Earth to a reasonable size. Soller slits exclude a large part of the incoming sunlight, decreasing the overall efficiency significantly.

III.IV System Trade-off

In the system trade-off the drawbacks of all three concepts are evident. Therefore it was decided to come up with a concept combining the advantages of the three designs. The resulting concept (Fig-2) was named after the courier of the Sun in classic Mithraic ceremonies: 'Heliodromus'. A broad area of technology and its disciplines are involved like collecting optics, solar cells, deployable structures, microwave and antenna technology and attitude- and orbit control to obtain the required pointing accuracy. Moreover costs. sustainability and reliability play a key role in the system-trade offs. A glimpse of the Systems Engineering approach is given in the flowcharts given by the Figures 3, 4 and 5.



Fig-2: The Heliodromus SBSPS



Fig-3: Functional Flow Diagram of the SBSPS



Fig-4: LEO Functional Breakdown Structure.



Fig-5: GEO Functional Breakdown Structure.

A single GEO satellite has five mirrors, one for each LEO satellite. The LEO satellites collect the Sun's energy and transmit it by means of lasers to the mirrors in GEO, which redirect the light to Earth in return (Figure-2). Heliodromus has the advantage of having only little mass in GEO, as most of it is in LEO.

The contact time with the ground stations is permanent, i.e. the energy supply is continuous. Moreover, the system is easy scalable, requiring only a small mirror satellite to be launched to GEO for each new LEO satellite. An artist impression is given of the system design of both the LEO satellite and the GEO satellite in Fig-6 to 9.

For an end-of-life power output of 1 GW on Earth, a total surface area of 3.44 km² of thin film photovoltaic cells is needed per LEO satellite. The photovoltaic conversion is limited by a 15% end-of-life efficiency. Thin film panels are applied which are cheaper to produce and have a large power and package density compared to other PV cells [16]. Consequently, less launches will be needed. Another advantage of thin film is that it is easy to assemble and maintain, which will reduce the overall cost.

The LEO satellite, shown in Fig-6 and 7, consists of two extremely large solar arrays, both 1.72 km2 in size. These arrays are build up from 76 separate deployable thin film solar panels. The two arrays are positioned in such a way that they will never obstruct the laser beam which has a maximum deviation of about 10 degrees. This is seen in Fig-7 which shows the two solar array wings of a LEO satellite as subsystem of the Heliodromus SBSPS.



Fig-6: Solar array configuration of the LEO satellite.

Two arrays are chosen to limit the amount of cabling for energy transfer to the laser system positioned in the center of the satellite. Each array is connected to a separate laser constellation consisting of 200 lasers. The upper laser system differs from the lower one since it can point the lasers directly towards the focal point of the first mirror. The lasers are placed under an angle in a large circle to provide clearance for the rotating second mirror and still be able to beam the lasers through this focal point. For the upper lasers the cooling can be located on the inside of the laser system attached to the laser support structure. On the lower side the cooling for the lasers can be located in a similar manner only here on the outside of the lasers. The arrays and the laser constellation are connected by the support structure of the rotating mirror. Since this structure is rotating along with the mirror the arrays can also rotate with respect to each other, hence both arrays need their own attitude determination and control system (ADCS) to be able to point both arrays towards the Sun. This can be easily integrated in the trusslike support structure of the solar arrays, where also standard control systems needed for satellite operations can be accomodated.

The generation of the laser beam for wireless power transmission [17] is done with an efficiency of 60% and each individual laser has a power output of 1 MW at an IR wavelength of 1064 nm. In total, the system of ten LEO satellites uses 4000 lasers. The choice for laser on Heliodromus instead of microwaves transmission is made, because of the huge antennas and rectennas required to generate power in the order of Giga-Watts. Already existing studies on the subject by NASA and ESA only covered microwave, hence a concept using laser transmission was open for out of the box thinking. Moreover microwaves have a safety concern in case of a misdirection.

A mirror system on the LEO satellites, using mirrors with a diameter of 9 meter and 12 meter, bundles all separate lasers rays to a single beam and directs it to the GEO satellite (Fig-9). The LEO satellites have a permanent contact time with one of the two GEO satellites, switching between them when needed. The GEO satellite, having five mirrors of 24 m diameter each, reflects the energy to the associated ground station, providing energy to Earth continuously.

The laser beam travels through the atmosphere [13] with an efficiency of 85% and reaches the Earth's surface at two ground stations, located in Arizona, USA and Egypt, North Africa. These areas are selected considering cloud coverage and aerosol density, seismicity and political stability.

At the ground station the laser beam is converted by means of monochromatic photovoltaic cells, optimized for the wavelength of the laser [18,19]. This conversion can be performed with a conversion efficiency of 40%, resulting in a power output of 500 MW per ground station.

The Stirling or Brayton engine [20] is the best option for solar dynamical conversion at a lower efficiency of 31% but its mechanical reliability is questionable for space applications. Therefore PV arrays are favourable.

The GEO satellite, shown in Fig-8, consists of five separate mirrors which need to track and trace the compliant LEO satellites. Therefore it is needed for each mirror to have an individual ADCS. The mirrors are connected by a truss like structure to the central part of the GEO satellite, which accomodates all the necessary subsystems, like another GEO S/C ADCS.

The power supply for these systems is obtained from the laser beam by using solar cells located on the borders of the mirror [21]. The laser transmission from the LEO to GEO spacecraft is shown in Fig-9.



Fig-7: The LEO subsystem of Heliodromus.



Fig-8: The GEO subsystem of Heliodromus.



Fig-9: Laser transmission from LEO to GEO

V SYSTEM PERFORMANCE

The performance of Heliodromus was evaluated by evaluating the following parameters:

- 1. Technological Readiness Level(s) (TRL).
- 2. Total (chain) efficiency.
- 3. Integral costs.
- 4. Energy payback time.

A performance comparison between Heliodromus and Earth based solar farms was made to see whether Heliodromus could be competitive with conventional renewable energy sources.

V.I Technological Readiness Levels

Main bottlenecks in the applied technologies are the laser and the thermal subsystems. The required 1 MW continuous wave lasers are not yet available and especially not with a lifetime of 10 years or higher. The 60% efficiency of the laser results in 40% energy loss. This wasted heat has to be rejected by means of thermal radiators. The amount of required radiating surface is huge, contributing for 50% to the mass and volume of the LEO satellite. Therefore, improvements on either the efficiency of the laser or the effectiveness of the thermal radiators shall be made. Furthermore, to increase the overall efficiency of Heliodromus, the efficiency of both photovoltaic cells and lasers has to improve further.

V.II Overall efficiency

The overall efficiency of the Heliodromus concept is estimated to be approximately 2%, based on a power input and output of respectively 47 GW and 1 GW. The major losses occur during the initial energy conversion by the photovoltaic thin films in space, which have an efficiency of only 15%. The conversion of electricity to IR laser light is assumed to be done with a state-of-theart efficiency of 60%. The ground conversion of laser IR light into electricity significantly contributes to the

V.III Total costs

To be market viable the electricity price of Heliodromus has to be about 0.1 \$/kWh, as concluded in a market analysis. The total cost of Heliodromus is estimated to be about \$98 billion, of which nearly \$80 billion are the costs of the laser devices and the launches. The resulting electricity price of Heliodromus is approximately 1 \$/kWh. This value is based on the most pessimistic mass estimates, i.e. the highest launch costs with a total of 1200 Ariane launches.

V.IV Energy payback time

The energy payback time for the Heliodromus concept is estimated using the following division: the collection system, the transmission system, the ground station and the launch. This led to a total energy payback time of approximately 6 years.

Another major concern for *Heliodromus* is the assembly of the satellites in space. The dimensions of both the LEO satellites and the reflectors in GEO are of such an order that they do not fit into a single launch vehicle. For this reason assembly in space is required to create the complete structure. Since the assembly involves thousands of parts, the assembly of these parts and the realization of the large amount of launches in a short time frame will become a big challenge [22, 23].

 Table-2: Comparison with Earth based solar farms.

	Average Output [GWh/year]	Costs [million \$]	Lifetime [years]	Output [\$/kWh]
Heliodromus (PV)	8800	89000	10	1.01
Moura Spain (PV)	93	325	20	0.17
Waldpolenz Germany (PV)	40	170	20	0.21
Andasol Spain (SD)	180	390	20	0.11
Nevada US Solar One (SD)	134	266	20	0.10

V.V Comparison with Earth based solar farm

When Heliodromus is compared to already existing solar farms, both photovoltaic and solar dynamic (SD), Heliodromus is 5-10 times as expensive (Table-2). For an Earth based system the energy payback time [24-26] ranges between 1 to 2.7 years, compared to the 6 years for Heliodromus.

VI Conclusions and recommendations

Heliodromus is a result of a concept exploration. By means of a subsystem analysis three concepts were proposed. Trade-off between these concepts resulted in the selection of a fourth concept, as a combination of the other three. Heliodromus is a constellation consisting of ten satellites orbiting in LEO and two modules orbiting in GEO having five mirrors each. The number of satellites in LEO is scalable depending on the energy demand on Earth. For each added LEO satellite a mirror must be launched to GEO. The LEO satellites are in a 1400 km orbit. The locations of the ground station were determined by evaluating cloud and aerosol densities, seismicity and political stability of the region. The trade-off between these criteria resulted in the selection of two regions: Arizona, USA and Egypt, North Africa.

An estimate of Heliodromus' total efficiency resulted in a value of 2%, which is not sufficient to compete with Earth based solar systems. Heliodromus' energy payback time is 6 years, which is within the minimum lifetime of 10 years, but longer than the energy payback time of the Earth based system. The total rough-order-of-magnitude (ROM) costs of Heliodromus are \$98 billion. At this stage it can not be price competitive with Earth based fossil nor renewable energy sources. Existing solar farms are already 5 to 10 times cheaper, at around \$10-20 cents/kWh compared to the \$1/kWh for Heliodromus.

Concerning the gound photovoltaic subsystem, an efficiency of 40 % was assumed. By beaming the laser on a different wavelength [1048 nm] the efficiency in lab conditions is already 60% and may rise to 80% [6].

The major technological bottlenecks are the laser size, efficiency and performance. Coupled to this problem is the size and mass of the thermal radiators required for the LEO satellites. Further developments in PV cell efficiency can significantly reduce the required mass and volumes for launch to space. In addition, assembly in orbit has never been done on the scale needed for Heliodromus necessitating a totally new field of research and development. These costs are not included in the estimates, therefore autonomous deployment was considered.

Table-3: Subsystem efficiencies.

Component	Efficiency [%]	Future Efficiency
Thin Film PV [space]	15	30
Laser	60	70
LEO mirror	99.5	99.5
GEO mirror	99.5	99.5
Airy disk spot mirror	84	84
Atmosphere	85	85
Airy disk spot [ground]	84	84
Si PV / Converters [ground]	40	60-80
Overall Efficiency	2.14 %	7.48 - 10.0 %

Current and possible future efficiencies are given in Table-3. The total efficiency can be improved up to a factor 5 in the near future, getting Heliodromus closer to market viability.

Formation flying in combination with novel lightweight structures of nano-sats enlarges the scope of SBSP design trade-offs. Both options are part of intensive research at the TU Delft, faculty of Aero-Space Engineering. SBSP studies are proceeded at DSE level.

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