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# SunSat Design Competition 2013-2014 First Place Winner – Team Rajiv Gandhi University: HelioAstra

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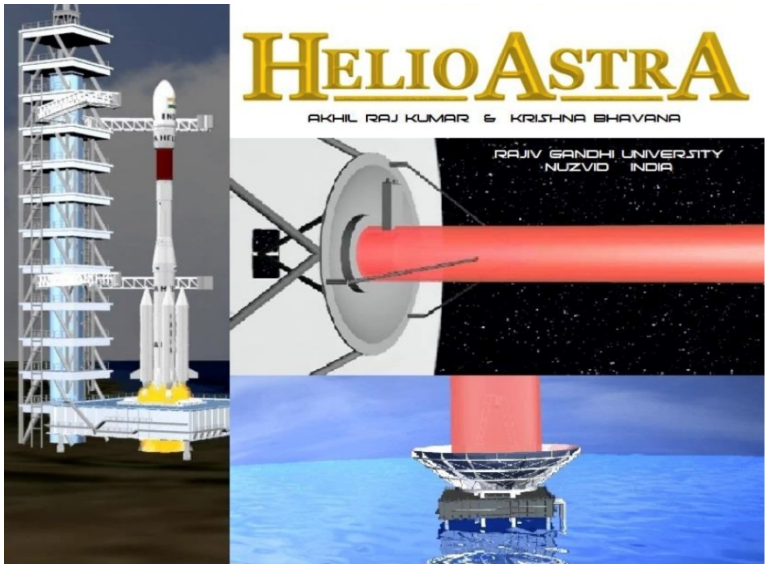


**HelioAstra**

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## ABSTRACT

HelioAstra is a creative design and visualization of an advanced Space Solar Power system. Its concept is validated by a credible science and engineering approach and an innovative business plan.

The space and ground receiving segments are made up of high efficiency Fresnel lens concentrator quantum dot solar cells. The solar array in space is sized at 933 m2. It delivers 1 MW (1000 kW) of perennial, clean and eco-friendly solar electric power at the bus-bars on the ground.

A solid state laser system containing Neodymium doped Yttrium Aluminium garnet (Nd: $Y_3Al_5O_{12}$) will accurately and efficiently transmit power. A ground receiving station with 70m diameter rectifying antenna will collect the power delivered in the form of a laser signal and energize the Sea Water Reverse Osmosis (SWRO) Desalination plant located in the Bay of Bengal near the Indian costal metropolitan city of Vishakhapatnam in the state of Andhra Pradesh.

Two Ku band transponders with uplink signal - of intelligent design – will continuously track the HelioAstra SunSat and respond as per Motion Control Facility (MCF) instructions. Being placed in Geostationary orbit helps the satellite maintain a fixed beam footprint on the earth's surface around the clock.

An innovative marketing strategy will enable value addition by a factor of 80 times based on the sale of solar electric power delivered from the HelioAstra solar power spacecraft and sale of 1.734 million litres/day (MLD) of fresh water produced by an SWRO desalination plant.

The HelioAstra SSP System Efficiency Chain and the integrated HelioAstra–Aqua (SSP-SWRO) overall System, Mission Efficiency and Performance Chains are presented using open-source published values of component efficiencies.

The cost of space segment and ground segment (including ground power receiver and salt water reverse osmosis plant) and annual revenue flow are estimated based on a sensitivity analysis on Excel spread sheet. Revenue value-addition by use of SWRO for production and sale of fresh water and use of the advanced Falcon 9 (Reusable) space launch vehicle are required to enable acceptable system specific costs within a mission-investment payback period of 7 years.

## TECHNICAL BRIEF

## INTRODUCTION

"The humanity needs a great vision to forget all the conflicts and move towards a common goal of peace and prosperity for all the global citizens. We visualize the birth of world vision leading to "livable planet earth". This vision will be greater than any other vision so far envisioned by the humanity"

- Dr. APJ Abdul Kalam ISDC San Diego, 2013

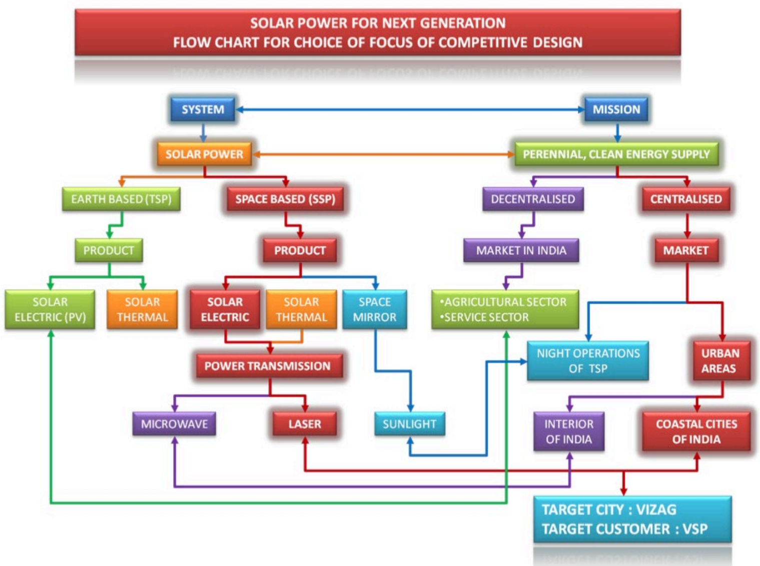
Man's quest to explore the unknown has unveiled many mysteries of the universe over the past century. This pursuit has changed the face of technological innovations and produced innumerable inventions of significance, among them being "electric power."

Energy in the form of electricity has become the driving fuel for the engine of human lives. Based on the enormous and growing number of consumers of electrical power and power appliances, we are seeing major growth in demand for new sources of energy. In this scenario, our rapidly deteriorating natural resources, increasing population and high levels of pollution are adding to the strain of living on earth. There is a need for viable alternatives. We can look at Space Solar Power as one such remedy, a perennial source of clean energy that could also usher in a new era of peace and prosperity for mankind.

HelioAstra, an innovative engineering design, proposes a technologically plausible, economically feasible, environmental friendly alternative to the power crisis the world is facing today.

HelioAstra is a solar power satellite (SunSat) designed to capture sunlight 24x7 in space. This satellite will convert sun's rays into electricity using Fresnel lens concentrator quantum dots doped solar cells transmitted via a laser beam to ground.

In this application, to make it a viable business plan we propose that the value added end product of this electricity be "desalinated fresh water."




The above flow chart notes the scope of space-based solar energy production and various business strategies that might be adopted. The terms and paths highlighted in red represent the system and mission plan adopted by HelioAstra. The chart suggests the advantages of space solar power over terrestrial solar power, solar electric over solar thermal and solar mirrors. In this case, the mode of power transmission is via lasers rather than via microwaves.

To make the project economically feasible, we have chosen a centralized mode of market over a decentralized market within an urban coastal area of India for easy transportation of desalinated, de-mineralized fresh water. Keeping in view the serious technical and social issues that the regional Vizag Steel Plant (VSP) is facing due to water scarcity, HelioAstra's target customer is this company, located in the costal metropolitan city of Vishakhapatnam in the state of Andhra Pradesh. The region has a great need for fresh water that can be made available near the coast.

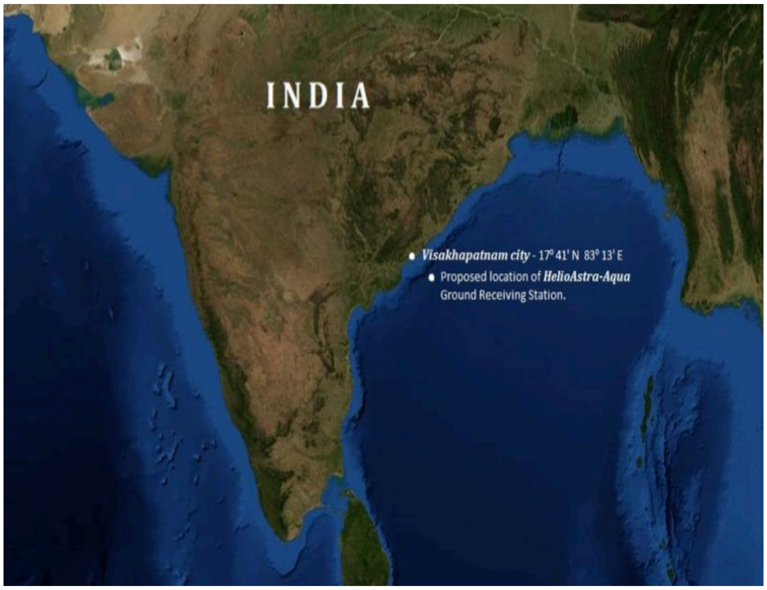



Image1: Map showing the proposed location of HelioAstra-Aqua Ground Receiving Station

Image2 : Visakhapatnam Seaport and coast - Ariel View

## DESCRIPTION OF SSP SYSTEM

HelioAstra is a next generation SunSat that consists mainly of two segments: a space segment and a ground segment. The space segment is the PowerSat itself with huge solar arrays placed on a square rigger base. The solar arrays are composed of Fresnel lens concentrated quantum dots doped solar cells.

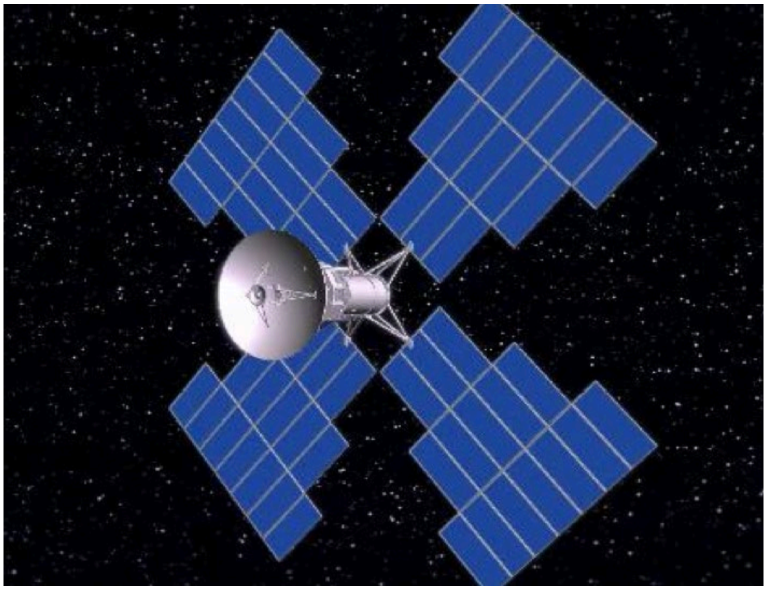


Image3 : HelioAstra Space Solar Power Satellite

To reduce the cost and increase the efficiency of the solar cells in space, the plan is to minimize the solar array size and focus the maximum amount of solar light onto small cells using concentrator optics. In the HelioAstra design, stretched lens array arched Gallium Arsenide mini-dome Fresnel lens concentrators are used to maximize the amount of sunlight incident on each cell, and quantum dots are used to increase the efficiency.

These Fresnel lenses are laminated with 75 micron-thick ceria doped glass arches and a multi-layer oxide coating (to avoid the direct incidence of solar ultraviolet radiation) of mono-atomic oxygen on the cells, thereby protecting them from being damaged. In addition, HelioAstra uses monolithic triple layered p-n junction photovoltaic cells with Quantum dots producing bandgaps of 1.89, 1.42, and 0.94 eV placed in the focal lines of the Fresnel lenses. Thus, the maximum amount of sunlight is incident on these relatively small solar cells of our HelioAstra PowerSat.

The stretched lens array square rigger (SLASR) technology HelioAstra adopted is an advanced version of stretched lens array (SLA) technology in which the lenses are tensioned lengthwise between end arches for lens arrangement and support on orbit, unlike the fragile, bulky and expensive glass arches used in SLA. This ultra-light concentrator array provides the benefit of a very compact volume and a flexible blanket version of SLA technology.

In HelioAstra adopted SLASR technology, the carbon composite structural tubes are arranged in a very compact manner occupying less volume. These tubes are formed into rectangular bay structures of about 3.12 m x 5.0 m each and are locked followed by the radiator blankets pulling across the frame to form the complete SLASR array. Each bay is capable of producing 16.7 kW of power. The components that weigh the most in the array are the lens and radiator that contribute to 70% of total array mass.

The three key concepts that enhance the quality of HelioAstra's power system and make it the best choice are: 1) Stretched Fresnel lens, 2) Quantum dots, and 3) Multiple junctions.

**STRECHTED LENS**

The stretched Fresnel lens helps in enhancing the optical efficiency of HelioAstra's solar cells. In the case of this PowerSat using the stretched lens square rigger, the Fresnel lens are stretched lengthwise between end arches to direct the sunlight directly on the solar cells, thus, the amount of sunlight incident is maximized resulting in greater output. Mini dome lens provide the highest performance and least degradation and the pop-up arches arranged in the layers make them self-stressed membranes without the use of glass arches reducing the weight and occupancy of the cells.

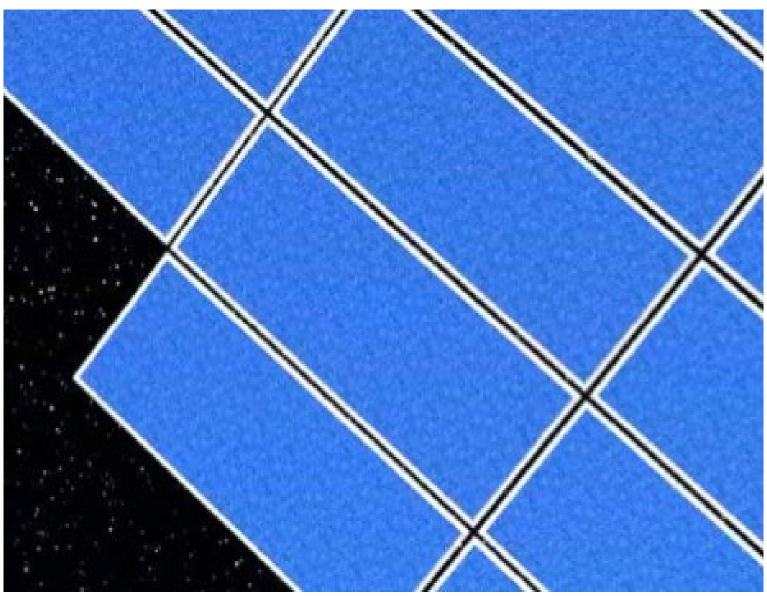


Image4 : Stretched Lens Array

These cells have high-voltage operational capabilities and the ability to withstand a high-radiation environment, which is crucial as our satellite is placed in

Geostationary earth orbit (GEO). Due to this, 85% of cell area is saved, giving room for a larger number of cells to be installed. SLASR technology is bestowed with such improvised qualities as lightweight, compact, thin film, high efficiency, less complex, rigid and cost efficient. The cost of this type of arrangement is only 50% of the planar multi-junction arrangement.

## QUANTUM DOTS

Quantum dots doped solar cells of HelioAstra are used as the photovoltaic material in contrast to traditionally used copper, gallium, and so on. Quantum dots can be tuned to produce various bandgaps for the PowerSat without changing the underlying material, but only by altering the size of the dot unlike the other ones where the bandgap depends on the material used and is fixed. Quantum dots are often proclaimed as artificial atoms having multiple electron energies in them.

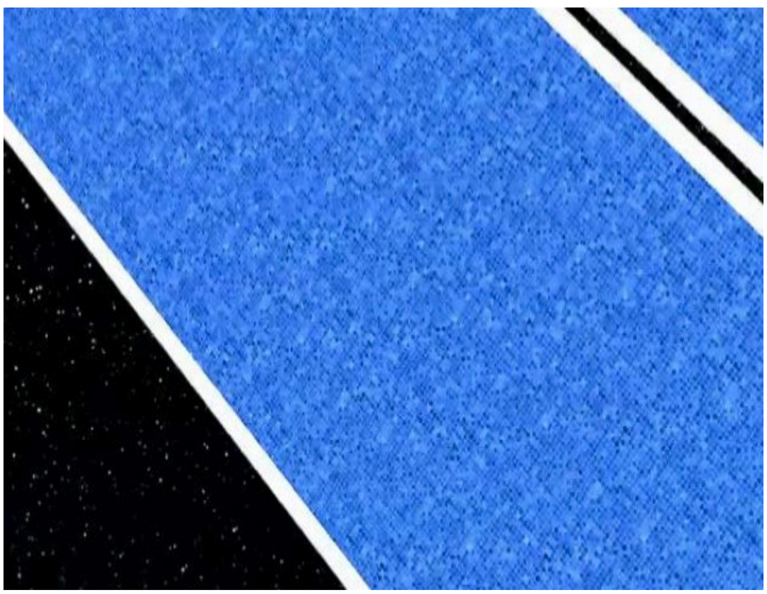


Image5: HelioAstra SunSat Space Solar Array

Most of the sunlight that is incident on the satellite in GEO is in the infrared and near-infrared region. Capturing this light using traditional semiconductors becomes difficult; but with quantum dots technology, IR sensitive materials can be made very easily, enabling HelioAstra to capture more energy at lower cost. Quantum dots reduce the heat loss and help in converting the whole amount of energy into useful form. With all its benefits and superior properties, quantum dots enhance the efficiency of normal photovoltaics and, in turn, the overall efficiency of our energy production system.

## MULTIPLE JUNCTIONS

Multiple junctions enable our HelioAstra system to absorb the maximum amount of energy produced by Sun. This is achieved by tuning the quantum dots to various bandgaps. Sunlight spectrum has many colours. Multi-junction solar cells of our system will be designed with different bandgaps in correspondence to the incident photon energy to absorb the diverse energy produced in different colours as the energy is absorbed only when the bandgap of absorbing material is equal to photon energy. Multiple bandgaps enable HelioAstra cells to absorb maximum energy from the various frequencies. They also provide the path to high efficiency.

## LASER BEAM TRANSMITTER

As the designated Geostationary orbit is some 36,000 km above earth, laser beaming is an extremely risky medium for power transmission. It needs high accuracy, good directivity and a small footprint on the earth's surface.

Given these constraints, to have an efficient transmission system, our HelioAstra solar power satellite designers have opted for a Laser Diode technology. Solid state lasers like Neodymium doped Yttrium Aluminium garnet (Nd: $Y_3Al_5O_{12}$) made of synthetic mono-crystalline material are highly efficient high power laser transmitters. Yttrium Aluminium garnet (YAG) is the host (base) material doped with neodymium having doping concentration of 1.4 molar percent to enhance low-power continuous-wave lasers as well as high-power Q-switched (pulsed) lasers with power levels ranging from kilowatts to megawatts. Nd:$Y_3Al_5O_{12}$ has high thermal conductivity and fluorescence, and produces infrared light at a wavelength of 1064 nm.

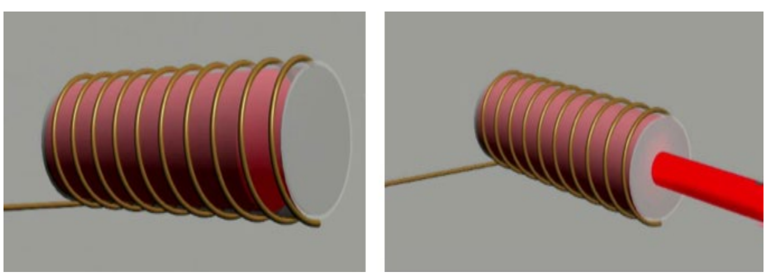


Image6 : Solid state Neodymium doped Yttrium Aluminium garnet laser

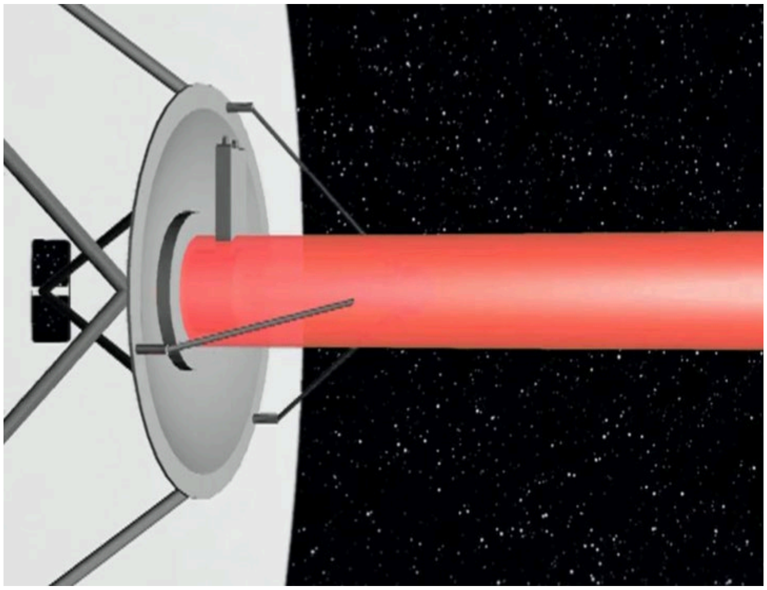


Image7 : HelioAstra SunSat Laser Beam Transmitter

**TRANSPONDER**

In this proposal, 2 Ku band transponders are mounted on the HELIOASTRA SunSat for interactive communications. These transponders serve the purpose of tracking and controlling from the ground such spacecraft activities as motion, transmission and altitude. To reduce power consumption, they are designed only to respond to an uplink signal. Unlike the broadband signal transponders of communication satellites, their purpose is limited to tracking and controlling the HelioAstra satellite, based on commands it receives from a Motion Control Facility (MCF) situated on the ground. The downlink signal is carried via the laser beam (along with its power transmission). A photo-detector is installed at the receiving site to decode the optical signals. These Ku band transponders will work in the frequency range of 12.7-14.5 GHz, each consuming 30-50 watts of power.

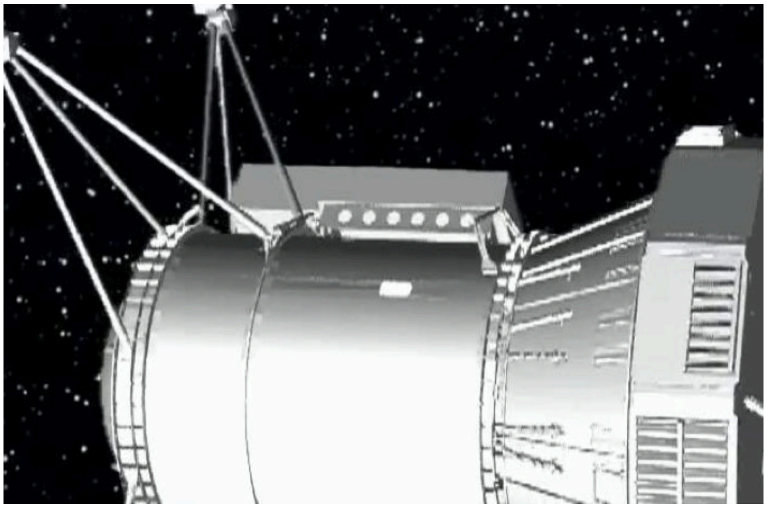


Image8 : Transponder installed in HelioAstra SunSat

**GROUND RECEIVING STATION**

The ground receiving station - the earth segment of power production - is equally important. The power delivered to earth in the form of a 287.28 kW laser beam (with transmission efficiency of 0.90) is captured by a disc shaped concave ground rectifying antenna contained within a collecting area of 3900 m2 with gain of 171 dB (Diameter of receiver dish = 70 m). The receiver is designed to be parabolic to increase its surface area.

It is an observed fact that out of the whole beam incident area on the receiver antenna more than 90% of the intensity is concentrated on the 'Y' shaped area within the beam footprint on the antenna disc, accounting for only 1/3rd of the whole antenna area. To have a reduction in construction cost here only at the 'Y' shaped area where the maximum intensity is concentrated, high efficient quantum dots doped cells are placed to capture the laser beam energy and to convert it into electricity, the final product of energy transmission. This reduces by some 3 times the expenses incurred in construction and reduces reception losses.

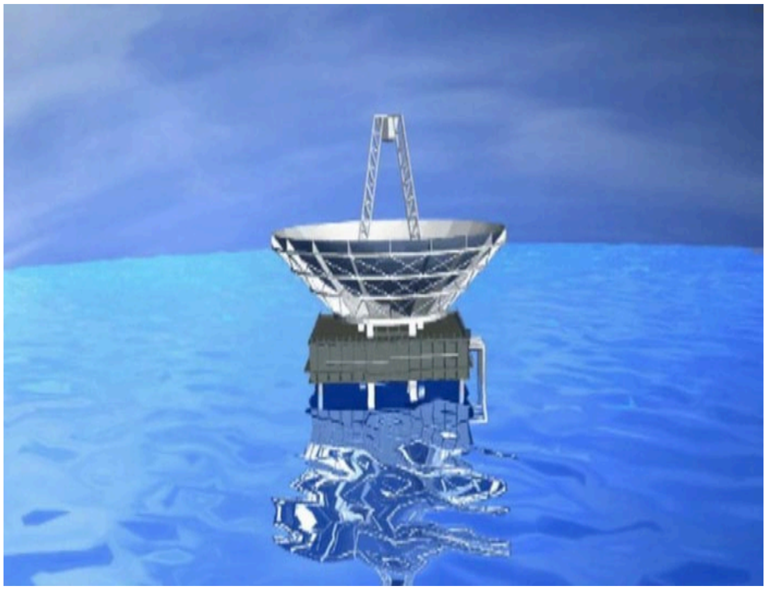


Image9 : Ground receiving station in Bay of Bengal

**How the HelioAstra SunSat Works**

When the sun's rays of 1.41 kW/m2 high power intensity incident on the 933 m2 large solar arrays, the electrons of band gaps 1.89, 1.42, and 0.94 eV in quantum dots doped gallium arsenic (GaAs) solar cells are provided with enough energy to get excited free from the semiconductor, resulting in the production of electric current with an efficiency factor of 0.76. The electric current thus flows through carbon composite structural tubes connected to the solid state Neodymium doped Yttrium Aluminium garnet laser transmitter. This solid state laser converts raw electric power into laser format, producing a laser beam with an efficiency of 0.42. The output laser beam power is 319.2 kW incident on transmitting antenna, amplified and consequently shot towards earth. On the earth, the receiving ground station - a 70 m diameter disc rectifying antenna - collects the transmitted 287.28 kW power in the form of laser beams and converts it into 229.82 kW of electric power.

**JUSTIFICATION FOR CHOICE OF LASER TRANSMISSION**

It could surely be argued that SSP application for seawater desalination would be even more profitable with microwave transmission. So why go in for laser power transmission?

Even though SSP with laser power transmission is heavier and costlier than SSP with microwave power transmission, we remain firm in our choice for the following reasons:

1. ***Pointing Accuracy***: For seawater desalination plants along the coastline, pinpoint accuracy is needed to energize and operate SWRO systems using space-based solar power. This level of pointing accuracy is not feasible with microwave power transmission.

2. ***Safety***: In the short term, safety in power transmission from space is a key criterion for mankind to enter into a new era of harvesting energy from space. Placement of the world's first techno-commercial 1 MW pilot plant off-shore is the safest means to start up global interest in SSP.

3. ***Sensitivity to Weather***: Cloud cover is often cited as a limiting factor for laser beam powered SSP. However in this particular application, in which space solar power is to be used in the operation of seawater desalination plants, intermittent delivery of electrical power is less of a constraint. Electricity cannot be economically stored to offset power interruptions, but the clean water produced can be. The installation of water storage capacity is a least cost offset to the loss of beam during cloudy weather.

4. ***Long Term Missions***: Once this pilot-plant for a revenue-earning SSP mission is firmly established and its operating data stabilized, the next step will be to further enhance laser safety for operating on land. The European aerospace firm Astrium is investigating new systems and technologies for transferring orbital solar energy to earth, and has considered using laser beams that operate at eye-safe wavelengths targeting specially equipped receivers on Earth. These on-board lasers will operate at powers that are comparable to a normal summer's day and therefore safe for humans and animals to walk through.

We remain firm in our choice of laser beam power transmission in preference over microwave beaming because of its credible short term and long term advantages.

## DESCRIPTION OF SSP MISSION

In spite of today's space technology available, present day space exploration and space power is still costly. In future Space Power may be expected to get as cheap as Terrestrial Power produced from fossil fuels, hydro electricity, nuclear plants etc. But for immediate realistic use it is too expensive. We are on the verge of extinction of fossil fuels, namely coal and natural gas but as their supply still exists the market for electricity has not yet become that expensive to be on par with the investment we made for the PowerSat. Consequently the electricity produced through this SSP also becomes expensive and needs a market to payback the investment. Now how do we match investment on HelioAstra SSP satellite and present day market cost of electricity? How do we make HelioAstra Space Solar Power a profitable Business Plan? To overcome the high cost of

Space Solar Power HelioAstra adopts a business plan where electricity is only an intermediate product and the value added end product that reaches the consumer is the FRESH WATER.

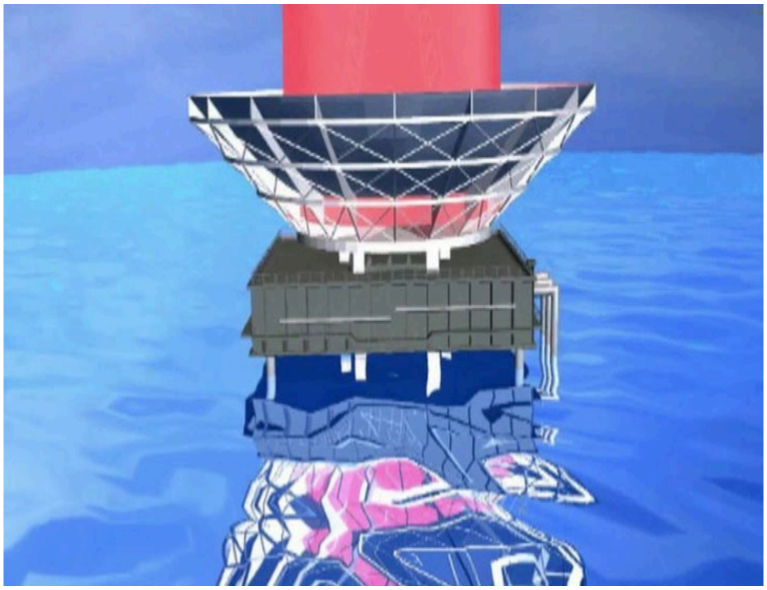


Image10 : Ground receiver with laser beam coming from HelioAstra SunSat

This Desalination plant is highly based on the Reverse Osmosis process to purify the saline brackish sea water.

**REVERSE OSMOSIS**

Reverse Osmosis Purification is the essence of HelioAstra-Aqua Purification Plant. Osmosis is a natural process in which water flows from high solute concentration to low solute concentration region trough a membrane until the concentrations on either side is equal.

The reverse osmosisvii as it sounds is the exact opposite of the osmosis process in which water flows from low solute concentration region to high solute concentration region through a semi permeable membrane. This is possible because of the hydraulic pressure generated by means of solar energy from HelioAstra Sat applied on the high concentration region. This pressure is applied to counterattack the osmotic pressure offered by the water. The semi permeable membrane only allows the solvent and all the impurities including the salts, pyrogens, bacteria and all the impure particles of molecular weight above 300 Daltons and larger than 0.1 nm are held back. This can also remove totally dissolved solids, turbidity, asbestos, lead and other toxic heavy metals, radium, and many dissolved organics which are the common entities found dissolved in Sea Water. The process will also remove chlorinated pesticides and most heavier-weight VOCs. RO is the best know process to desalinate the water. It also involves on the procedure of ionic extrusion.

The reverse osmosis filter of HelioAstra Desalination Plant is a combination of spiral-wound layers of semi-permeable membranes, the dense layers in the polymer matrix whose pore structures are very tight that they would not allow any larger particles except water. Care is taken to make sure that pore size is always less than 0.1 nanometers. RO guarantees the removal of 99% of all contaminants, to ensure maximum safety of the consumers HelioAstra adopts post treatment of RO, Ultraviolet purification as the third and final step of HelioAstra's water purification process.

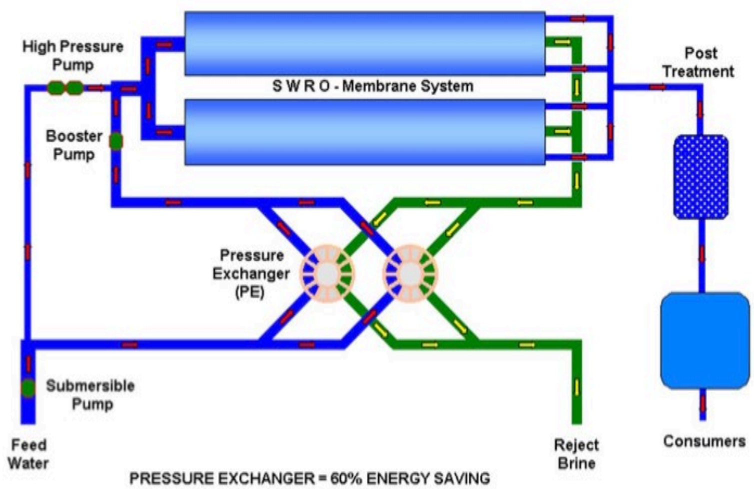


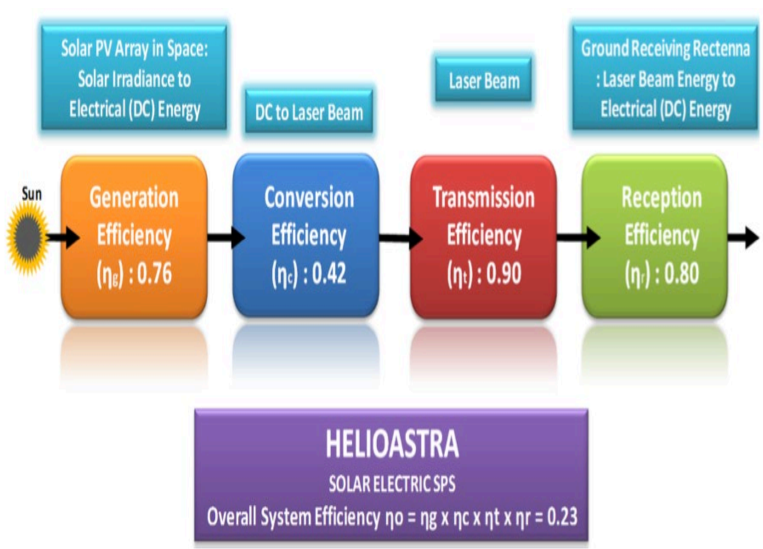

Image11: HelioAstra-Aqua Sea Water Reverse Osmosis Plant Working Model

## MISSION SPECIFICATIONS

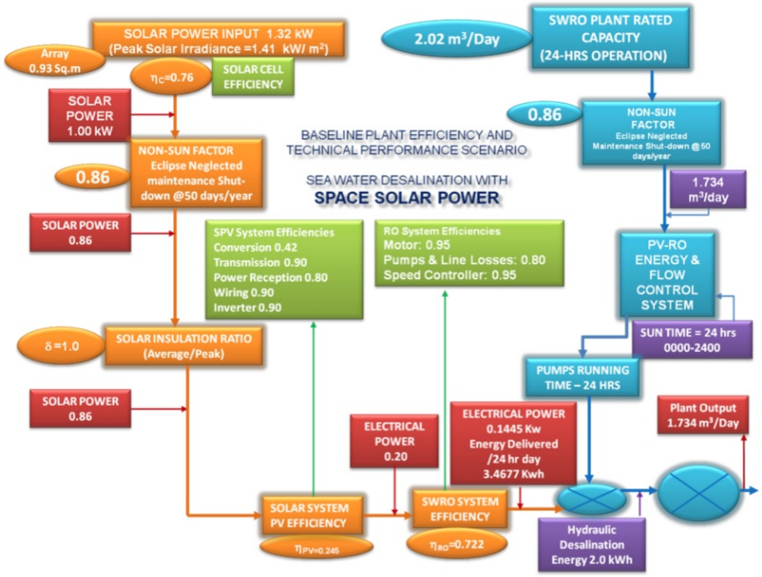
**Mission**: Domestic Market for Sale of Fresh Water in a Coastal Metropolitan City on India's East Coast

| *Serial No* | *Parameter* | *Value[7]* |
|---|---|---|
| 1 | Total system & mission cost | **$ 700 Million** |
| 2 | Assumed Specific Cost of SSP (Space Segment) | **$500,000 per kW** (Please see Annexure 4 for Methodology used) |
| 3 | Specific Cost of Falcon 9 (Reusable) Launch | **$1000 per kg in GSO** |
| 4 | Number of Falcon 9 (Reusable) Launches to GEO | **6** |
| 5 | Falcon 9 (Reusable) Payload in GEO | **4.68 tonnes** |
| 6 | Specific Cost of Ground Receiver | **$165 Million/MW** |
| 7 | Size of SWRO Plant | **2 $m^3$/day** |
| 8 | Fresh Water Produced | **1.734 Million Liters /Day** (MLD) @ $... per litre |
| 9 | Specific Energy of SWRO System | **2 kWh/ $m^3$** (fresh water delivered) |
| 10 | Allowable Specific Mass of SSP (Space Segment) | **28 kg/kW** [for payback of capital cost in 7 years without financing factors like interest on loan, taxes etc] |
| 11 | Specific Cost of Seawater Desalination Plant | **$5 Million/MLD** |
| 12 | Annual Revenue (through sale of solar electricity only @ Rs 10.00/kWh | **$ 1.26 Million** |
| 13 | Annual Revenue (through sale of fresh water) | **$ 105 Million** (@ Rs 10.00 per litre) or **$ 89.5 Million** (@ Rs 8.50 per litre) |
| 14 | Value Addition Ratio by Use of SWRO Technology | **80** (@Rs 10.00 per litre) **or 71** (@ Rs 8.50 per litre) |
| 15 | Payback period | **7 years** |
| 16 | Safety features | **Receiver is located off-shore in the ocean** |

## HELIOASTRA SYSTEM EFFICIENCY CHAIN



## OVERALL SYSTEM- MISSION EFFICIENCY AND PERFORMANCE CHAIN



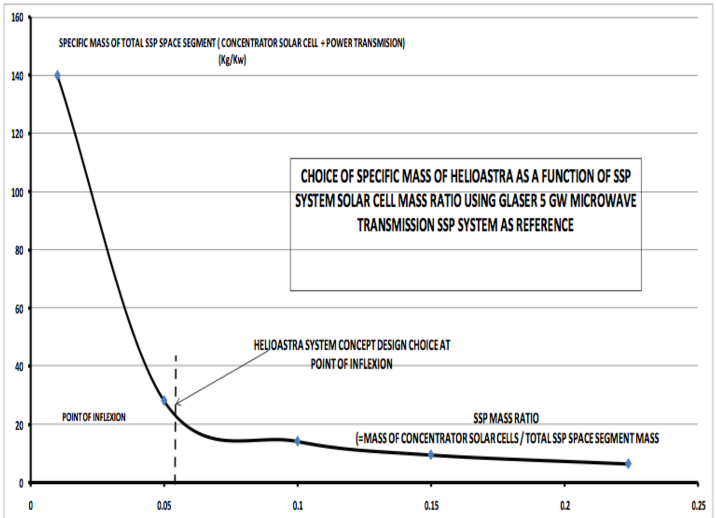

**Reference** : Solar Photo Voltaics Powered Seawater Desalination Plants [Suryajal Beijing Paper] by Dr.M.Kumaravel, R.Gopalaswami and team

## BUSINESS PLAN

## DESIGN-TO-COST APPROACH

**Specific Mass of HelioAstra**: To estimate the overall SSP system mass, we followed a Design-to-Cost approach. Since detailed component weight breakdown analysis of Laser SSP was not available in open literature, opinions were obtained from four leading US experts. The weight estimations provided by them varied from 10 kg/kW to 3000 kg/kW. The difference between minimum and maximum values was too high to reconcile. Hence, as part of our design-to-cost methodology, we separated the solar cell concentrator mass from the total SSP system mass for a reference satellite, taking Glaser P.E. "The Development of Solar power from Satellites" reference as base (0.224 Kg/Kw). We then varied different Concentrator Cell Mass to Total SSP Mass Ratios of SSP (from 0.224 to 0.01 Kg/Kw) to simulate higher and higher power transmission mass in a SSP satellite. Thereby, we deduced the specific mass of a complete SSP for different (solar cell + concentrator) mass ratios. This is shown in Columns 1 & 2 of Table 1.

On plotting these values graphically, it was seen (Graph 1) that the point of inflection occurred at SSP solar cell mass ratio of 0.05. Hence we have assumed the specific mass of concentrator QD Cells & Laser Power Distribution is 1.402 kg/kW, thus the specific mass of the HelioAstra SSP Sat will be 1.402 ÷ 0.05 = 28.04 kg/kW (for Mass Ratio of 0.05).




Graph1: SSP Mass ratio Vs specific mass of HelioAstra

**Specific Cost of HelioAstra:** Table 1 shows the overall methodology followed to understand the mass estimation of SSP Satellite as a function of SSP Mass ratio. HelioAstra space segment cost is taken as the *primary cost* of the total SSP system. The *secondary cost* includes a variable launch cost and sum of constant SWRO plant and ground receiving station cost.

We initially assumed the primary cost to be $500M, the highest value from among the 4 expert opinions. The sum of primary cost and secondary cost gives the Total Estimated HelioAstra-Aqua [SSP-SWRO] System - Mission cost. From Table 1, it may be seen that for a 1000kW (1.0 MW) HelioAstra SSP satellite with a specific mass of 28.04 tonnes/MW, requires 6 Falcon 9 [Reusable] launches to place it in GEO @ available launch cost of $1000/kg. We then used this system configuration to estimate the power economics.

| Mass Ratio of SSP (Concentrator Cell Mass/Total SSP Mass) | Specific Mass of Complete SSP System With Concentrator QD Cells & Laser Power Distribution (1.402/Mass Ratio) kg/kW | Power Output of SSP at Bus bars on Ground (kW) | Mass of SSP for Launch (tonnes) | Number of Falcon 9 - Reusable Launches for Payload in GTO = 4.68 tonnes | Cost of SSP Launch to GTO ($ m) FALCON REUSABLE @ $1000/- per kg | PRELIM ASSUMPTION | Cost of SWRO Plant ($m) | Cost of Ground Receiving Station ($ m) | TOTAL SECONDARY COST | Total HelioAstra-Aqua SSP-SWRO System Cost ($-m) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Cost of 1 MW HelioAstra SSP @ $500,000 per kW | | | Cost of SSP Launch to GTO + SWRO Plant + Ground Receiving Station ($ m) | |
| 0.224[iii] | 6.26 | 1000 | 6.26 | 2 | 9.36 | 500 | 5 | 165 | 179.36 | 679.36 |
| 0.15 | 9.35 | 1000 | 9.35 | 2 | 9.36 | 500 | 5 | 165 | 179.36 | 679.36 |
| 0.1 | 14.02 | 1000 | 14.02 | 3 | 14.04 | 500 | 5 | 165 | 184.04 | 684.04 |
| **0.05** | **28.04** | **1000** | **28.04** | **6** | **28.08** | **500** | **5** | **165** | **198.08** | **698.08** |
| 0.01 | 140.20 | 1000 | 140.20 | 30 | 140.4 | 500 | 5 | 165 | 210.40 | 810.4 |

Table1 : Estimation of overall mass of the SSP Satellite system using 'Mass ratio' technique under 'Design to Cost Approach' Methodology.

**Power Economics:** We compared the revenue flow from different water costs, considering the payback period to be 7 years. We do not know the specific cost of HelioAstra SSP space segment, but assuming the payback period is fixed to 7 years, and the cost of water is ₹ 10/litre, the annual revenue flow will be $105 Million, for 7 years $737 Million.

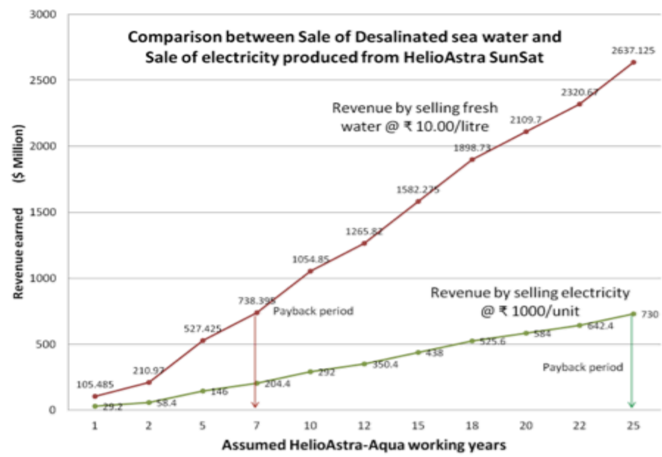
From this to determine the unknown, actual cost of HelioAstra SSP space segment could be 7 years revenue less secondary cost of HelioAstra system-mission i.e. $737 Million - $198.08 Million = $538.92 Million (if Concentrator Cell Mass to Total SSP Mass Ratio of SSP is 0.05). From that we can deduce the specific cost of HelioAstra SSP satellite to be 538,920 $/kW which closely matches to John Strickland's mentioned value of Specific cost.

Similarly, if the cost of water is fixed to ₹ 8.00/ litre and payback period is assumed to be 7 years, we have to design HelioAstra PowerSat at specific cost of 390,920 $/kW and 427,920 $/kW for ₹ 8.50/ litre with selected mass ratio of 0.05. Table 2 explains the revenue comparisons for different water costs in India, considering a payback period of 7 years.

| | AS PER PRELIM ASSUMPTION | | FRESH WATER COST  8.00/LITRE | | | FRESH WATER COST  8.50/LITRE | | | FRESH WATER COST  10.00/LITRE | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Mass Ratio of SSP *(Concentrat or Cell Mass/Total SSP Mass)* | Total HelioAstra-Aqua SSP-SWRO System Cost with Falcon 9 -Reusable Launcher. (1 MW HelioAstra SSP Sat Cost + Secondary cost) ($-m) | Output water from SWRO Plant (million litres / year) | Domestic Market Revenue for 7 year payback period @  8.00 /litre ($ million / year) | Target HelioAstra 1000 kW SSP Cost for 7-year payback period ($m) | Target HelioAstra Specific SSP Cost for 7-year payback period ($/kW) | Domestic Market Revenue for 7 year payback period @  8.50 /litre ($ million/ year) | Target HelioAstra 1000 kW SSP Cost for 7-year payback period ($m) | Target HelioAstra Specific SSP Cost for 7-year payback period ($/kW) | Domestic Market Revenue for 7 year payback period @  10.00 /litre ($ million/ year) | Target HelioAstra 1000 kW SSP Cost for 7-year payback period ($m) | Target HelioAstra Specific SSP Cost for 7-year payback period ($/kW) |
| 0.224 | 679.36 | 632.91 | 589 | 409.64 | 409,640 | 626 | 446.64 | 446,640 | 737 | 557.64 | 557,640 |
| 0.15 | 679.36 | 632.91 | 589 | 409.64 | 409,640 | 626 | 446.64 | 446,640 | 737 | 557.64 | 557,640 |
| 0.1 | 684.04 | 632.91 | 589 | 404.96 | 404,960 | 626 | 441.96 | 441,960 | 737 | 552.96 | 552,960 |
| **0.05** | **698.08** | **632.91** | **589** | **390.92** | **390,920** | **626** | **427.92** | **427,920** | **737** | **538.9** | **538,920** |
| 0.01 | 810.4 | 632.91 | 589 | 278.60 | 278,600 | 626 | 315.60 | 315,600 | 737 | 426.60 | 426,600 |

Table2 : Estimation of revenue flow for different water costs considering different mass ratio

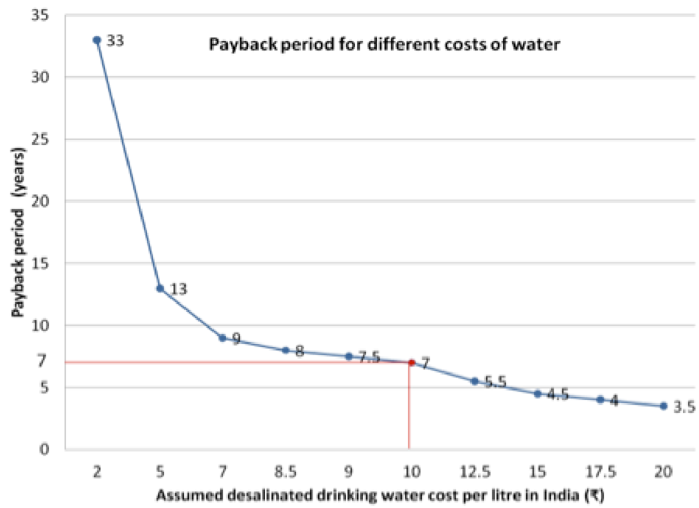
**Business Plan**: This project requires a strategy that is sustainable. Sale of produced raw electricity directly earns an annual revenue of $29.3 M, and takes around 23 years to payback the whole investment. However, the value added end product, desalinated fresh water, yields better profits. The HelioAstra PowerSat set up with a total investment of $698 Million produces 1000 kW per day which accounts to 313,900 kW per year (considering non-sun factors) and is used to energize an ocean-based desalination (SWRO) plant, of capacity 2.02 m3/ day with 24 hrs operation, to produce 632 million litres of fresh water per year. These 632 million litres of fresh water, when sold at a price of Rs.10.00 per litre, give a total revenue of $105 Million per year. As explained in Table 2, this mission is capable of producing a revenue of $737 M which is ample to payback the investment on the SunSat in 7 years.




Graph2: Comparison of revenue earned from sale of desalinated water and electricity.

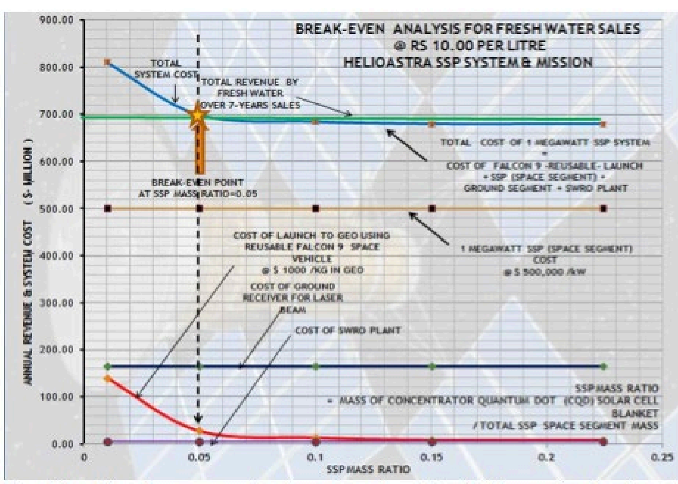
The above graph illustrates why HelioAstra has adopted and is focusing on the sale of fresh water (desalinated sea water) rather than the sale of electricity directly. The two curves plotted for the revenue from sale of fresh water at the current demand price (₹ 10.00 per litre) and for the revenue from the sale of electricity at present day practically impossible price (₹ 1000 per unit) make the huge revenue difference understandable. The slopes of two curves state the difference in margin between them. If plotted against the current price of electricity (₹ 7 per unit), the profit amplification factor happens to be 80.

**Payback period**: Keeping in view the water crisis persisting in countries like India, the price of water can easily go as high as ₹20.00 per litre, which is the cost most of the consumers are currently paying. Today in India the price may be a little less depending upon the abundance of water. A reasonable margin fresh-water-selling price can be expected to be ₹ 10.00 per litre. Sale of fresh water produced from the India desalination plant powered by the HelioAstra spacecraft promises to pay back the investment in 7 years, a reasonable and probably the least payback period that can be expected from a new innovative project.



Graph3: Payback period Vs Water cost

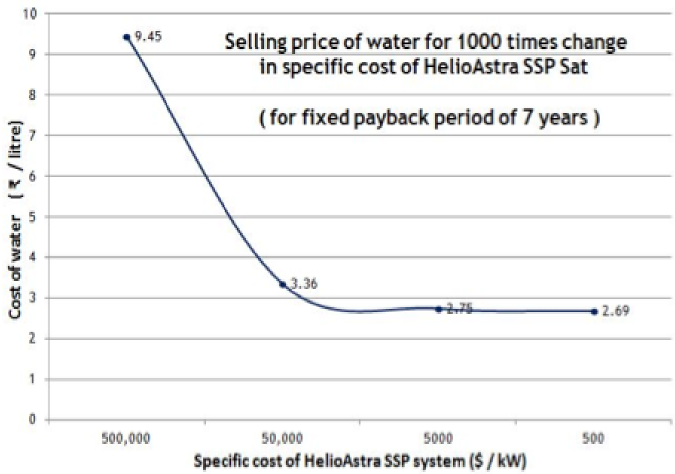
**Topology Graph**: A detailed analysis of the HelioAstra system and mission cost is shown in this topology graph. In this graph, the 'x' axis indicates *SSP Mass Ratio i.e. The ratio of the concentrator solar cell mass to the total SSP satellite mass* and 'y' axis indicates HelioAstra system cost. It shows at 0.05 mass ratio point, the break-even point, the red curve showing launch cost to GEO using Falcon 9 [Reusable] space vehicle shows exactly the launch cost to be $28 M and at the same break-even point the blue curve showing total HelioAstra system-mission cost exactly coincides with the assumed cost of $700 M.



Graph4: Topology graph showing the Break-Even Analysis of HelioAstra System-Mission cost.

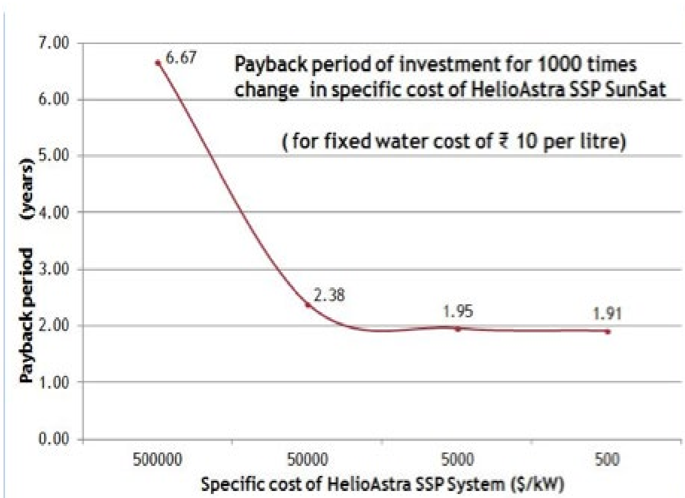
Considering this break-even point as the baseline to estimate the weight of the HelioAstra SSP Satellite, it turns out to be 28 tonnes and requires 6 launches to GEO using the above mentioned launch vehicle.

**Sensitivity Analysis**:We know the assumed specific cost of HelioAstra, $500,000/kW, is carried out for extreme high values to show that HelioAstra is feasible even at very high fabrication costs. As a part of our strategic business plan, let us consider the specific cost of HelioAstra SSP System reduced by 1000 times to $500 per kW. The sensitivity analysis done in the mentioned specific cost interval, i.e. from $0.5 M to $500, clearly shows that HelioAstra SSP system is economically feasible.




Graph5: Sensitivity Analysis carried for determining water cost for different specific costs of HelioAstra SSP System.

Reduction in specific cost to $500 per kW, reduces the selling price of fresh desalinated water to ₹2.69 per litre (as shown in Graph 5) still existing in the safe zone of economic feasibility for a payback period of 7 years.



Graph6: Sensitivity Analysis carried for determining payback period for different specific costs of HelioAstra SSP System.

Similar reductions in specific cost to $500 per kW, reduces the payback period of HelioAstra SSP system-mission investment to 2 years for a fixed water cost of ₹10 per litre (as shown in Graph 6).

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ENDNOTES

**Determination of specific mass of concentrator Quantum Dot Solar cells**

1. Specific Mass of QD Cells: 0.70 kg/kW - Bailey SG et al *"Inorganic Photovoltaic Materials & Devices"* NASA TM 2005-213341
2. Specific Area of Fresnel lens: 0.99 kg/m2 - NASA Hqrs Washington "*An International Forum on Space Solar Power*" Jan 12,2001 "*Mars SSP Satellite Power Link Budget,"* Table in Slide from Boeing
3. Solar Insolation in Space: 1.41 kW/m2
4. Specific Mass of Fresnel Lens: (= specific area /solar Insolation) = 0.99/1.41= 0.702 kg/kW
5. Specific Mass of Concentrator QD Cell = (A)+(D) = 1.402 kg/kW

**Expert opinion**

1. **Dr John Mankins** Personal Communication to R Gopalaswami 25 March 2014, $370,000 per kW for 3.1 GW laser SSP system.
2. **Keith Henson**, Personal Communication to R Gopalaswami 24 March 2014, $2500 per kW in the very far term with high volumes.
3. **Dr Narayan Komerath,** Personal Communication to R Gopalaswami 24 March 2014.
4. **John Strickland** Personal Communication to R Gopalaswami 25 March 2014, $500,000 per kW size of SSP not mentioned.

**SSP Mass Ratio**: The ratio of the concentrator solar cell mass to the total SSP satellite mass - developed from Glaser P.E. "*The Development of Solar power from Satellites*" Advances in energy Systems and Technologies, Vol. 2, Academic Press, New York, 1979. Volume 1. Table 3, Page 49.

Also from John Strickland, Personal communication to R Gopalaswami 25 March 2014 and from Narayanan Komerath, www.**ssp**i.gatech.edu/**ssp**_fundable_demo_hoffert.ppt

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C. **Narayanan Komerath**, Personal Communication to R Gopalaswami 24 March 2014
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