CARBON-NANOTUBE BASED SPACE SOLAR POWER (CASSP)

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Single Walled Carbon Nanotubes (SWCNT) are a product of advancements made in the field nanotechnology. Nanotubes exhibits a high tensile strength, high thermal & electrical conductivity, excellent field emission, radiation resistance and is an ideal diode. The latter property makes them one of the lucrative solar cell material available. The former properties make it ideal for use in a space environment and has been studied extensively for over 20 years. Recent advances in SWCNT manufacturing at NoPo, Bangalore, India, have made it possible for the material to be applied in real world applications at considerable costs. Usage of SWCNT based solar cells and electron emitters would substantially reduce the mass of energy harnessing systems by eliminating radiation shields, protection barriers and reducing weight of support structures & microwave transmitters. This is possible due to the inherent properties of the material. We make a case for space based solar power with a 50MW satellite that would weigh about 115tons if its core components were made of SWCNT. A modular design allows for this system to be built to full capacity over time using existing launch options at a cost of ~US$340 Million. The system would be profitable within 2 years of launch.

I. INTRODUCTION

The past three decades have seen a rapid economic growth in developing countries[1]. This growth is being powered by coal & fossil fuels. The downside of a coal powered growth is a suicidal destruction of our habitats due to climate change[2].

There are 6 billion people in less developed countries aspiring to live a life similar to the 1 billion in more developed countries[3]. This transition urgently requires a source of limitless clean energy. Failure to develop such a source could be catastrophic to the existence of humanity. According to the United Nations framework Convention on Climate Change, by 2050 we must produce clean energy equivalent to the total energy produced by every known energy source today[4] in order to limit human effects on the climate system.

SPACE SOLAR POWER

The Sun is the solar systems best clean energy source. It is the only functional nuclear fusion reactor. It has operated for several billion years and has been the source of limitless energy on earth. Some of the popular renewable energy sources such as hydroelectric and wind are derived from the Sun.

The space solar power concept entails capture of this energy in space and beaming it down to earth using microwave beams. This concept was first developed by Dr.Peter Glaser[5] and has been studied rigorously by various space agencies and individuals[6,7]. All of these studies have pointed out the technical feasibility of the concept. But this system is yet to be launched due to cost and other factors.

Problems preventing the immediate use of Space Solar Power

Existing Space Solar Power concepts have not been launched due to the following limitations in their designs:

1. A mass of 10,000-20,000 tons to produce 1GW of energy.
2. High satellite launch cost. Launching a 1GW SPS would cost several hundred billion dollars. A 1GW coal plant costs 1-2billion dollars.
3. Regular repair, replacement and maintenance of fragile, massive space structures.
4. High cost of space hardware. E.g.: Solar cells, high power microwave transmitters.

From the list of limitations, it is obvious that a big decrease in launch costs and space hardware costs are required to make space solar power satellite a reality.

SPS-ALPHA

Space solar power concepts have evolved rapidly during each energy crisis. The first version of the satellite entailed building a monolithic structure with a mass of over 100,000 tons. Such a gargantuan proposal could not gather support due to the enormous economic cost of such a project.

The most recent Space Solar Power concept is the SPS-ALPHA (Solar Power Satellite via Arbitrarily Large Phased Array) by Artemis Innovation[8]. This is the most practical space solar power concept to date. It breaks down the solar satellite into 8 small repeatable modules which are easier to launch, assemble and replace.

In this paper, we propose use of a product of nanotechnology; Single Walled Carbon Nanotubes to substantially reduce weight of modules to significantly decrease weight and cost. We also briefly discuss a 9th Module, The communication module that would provide functionality of a geo-synchronous communication satellite to the solar power satellite.

II. NANOTECHNOLOGY

Nanotechnology is the field of engineering that deals with objects, at least one of whose dimensions is of the order of a nanometer (10^{-9}m). This is close to the size of an atom. Nanotechnology allows engineers to engineer new materials with tailor made properties.

SINGLE WALLED CARBON NANOTUBE (SWCNT)

One of the most famous products of Nanotechnology research are Carbon Nanotubes. Carbon Nanotubes are an allotrope of Carbon. They belong to the family of Carbon called fullerenes. They were first identified by Dr.Sumio Ijima of Japan in 1991[9].

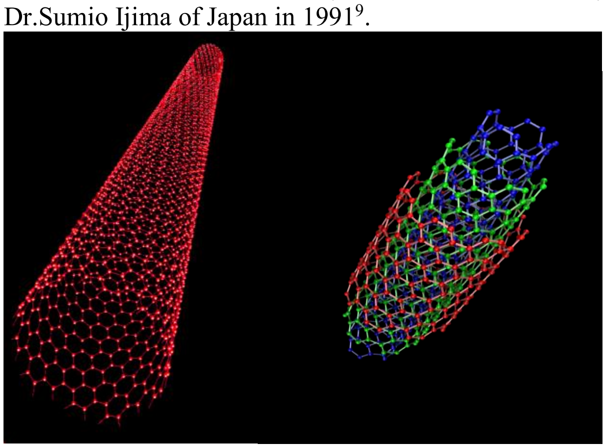

Figure 1: Two types of Carbon Nanotubes. (Left) Single Walled Carbon Nanotube. (Right) Multi Walled Carbon Nanotube

There are 2 types of Carbon Nanotubes: 1. Single Walled Carbon Nanotubes (SWCNT) and 2. Multi Walled Carbon Nanotubes (MWCNT). As their names suggest. An SWCNT is made of a Single tube of Carbon atoms as shown in figure 1. Depending on their diameters, SWCNT exhibit either semiconducting or metallic properties. Their properties can be precisely known and are the subject of this paper. MWCNT are made of multiple concentric tubes of Carbon atoms. They do not exhibit any semiconducting properties. They are already manufactured in multi-ton capacities and are mostly used in composites.

SWCNT have attracted a lot of attention due to their incredible material properties. They are one of the strongest materials known to mankind[10], they are more conductive than copper[11], have higher thermal conductivity than a diamond[12], are ideal diodes, are the best field emitters, are inert and radiation resistant[13]. This makes carbon nanotubes a perfect material for use in space applications.

Carbon nanotube based products that use these properties have been successfully developed in laboratories around the world[14]. Their path to markets has been limited due to high cost of SWCNT.

The main reason for the high cost of Single Walled Carbon Nanotube has been the notorious difficulty in purifying the material. This problem was solved recently by NoPo Nanotechnologies (NoPo) through the development of a proprietary continuous process that produces very high quality nanotubes at very low cost.

This breakthrough in production has made nanotube based electronic products practically viable. A Solar panel made of NoPo SWCNT would cost less than 2 US$ per square meter in Nanotube costs. Since carbon nanotubes can be semi-conducting or metallic based on their diameter. A complete solar cell could be fabricated using only SWCNT. Nanotubes are inherently radiation resistance. So there is no need for additional coatings. Due to their high tensile strength, they could withstand micro-meteor impacts with minimal additional reinforcements.

Figure 2: As-produced high purity Single Walled Carbon Nanotubes from NoPo Private Limited

III. CASSP SATELLITE

The Carbon Nanotube based Space Solar Power (CASSP) concept builds on top of the highly practical SPS-ALPHA. CASSP replaces some of the modules of SPS-ALPHA with much lighter SWCNT derivatives.

III.I Carbon Nanotube Solar Cells

A p-n junction diode exhibits the best possible photovoltaic effect. Single walled Carbon Nanotube are the only material that exhibit behaviour of an ideal diode. A 0.8nm diameter SWCNT with a band gap of 1.4eV would show peak absorption in the solar band. Such a cell is calculated to have an efficiency exceeding current multi-junction solar cells[15].

The thickness of the active Carbon layer required for such a cell is just 100nm[16]. A pure Carbon Solar cell would have a structure shown in Figure 3.

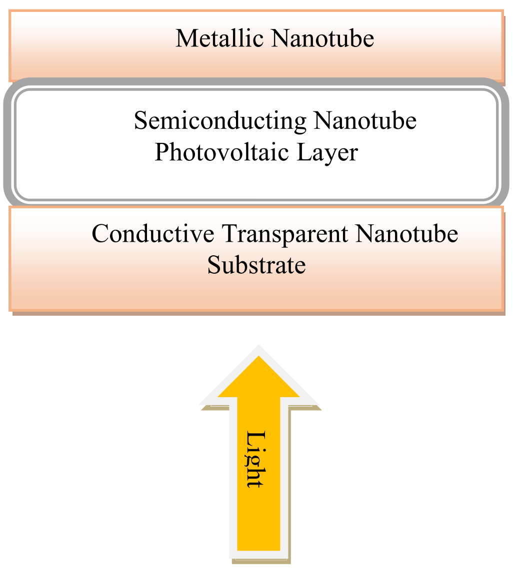

Figure 3: Block diagram of an SWCNT Solar Cell

Single Walled Carbon Nanotube based conductive transparent sheets have been fabricated successfully by several research groups. These polymers have radiation resistance and exhibit conductivity on par with existing ITO glass[17] [18] . The thin film avoids the brittleness of ITO thus ensuring a highly flexible structure. The thin film cell on a Polyethylene plastic substrate (density 0.91-0.96g/cm^3) has a thickness of just 0.25-0.5mm.[19]

A square meter of this cell would weigh just 230grams. In GEO, the average energy received is 1368W/m^2 [20] . Prototype SWCNT solar cells made in laboratories have already reached an efficiency of >10%. They are soon expected to exceed multi-junction cell efficiency of 35%. At multi-junction efficiency, these cells would produce 2W/gram.

The theoretical Carbon Nanotube Solar Cell is compared with a commercial Azur Space Solar cell in Table 1.

	Azur Space TJ Solar Cell 3G30C[21]	SWCNT Solar Cell
Base Material	GaInP/GaAs/ Ge on Ge substrate	Metallic SWCNT/Semi conducting SWCNT
Efficiency	30%	35%
Surface density.	<86mg/cm^2	<25mg/cm^2
Peak energy/Wt	0.046W/g	2W/g
Thickness	0.15mm	0.25mm
TRL	9	4
Cost/Watt	US$250	US$0.1

Table 1: Comparison of existing Solar cells with the proposed SWCNT solar cells.

The SWCNT solar cells are present on a flexible substrate and they do not require any additional reinforcements or support structures as is the case with GaAs Solar cells.

An SPS-ALPHA Solar cell Module using existing technology is estimated to weigh 15-20Kg for a 4m diameter Hexagon pod. An SWCNT solar cell module occupying the same area would weigh ~3kg and generate 6.3kw of energy.

The Hexbus module that provides support for the solar cells as proposed in SPS-Alpha weighs 25Kg and is made of a hollow tubular structure to provide rigidity and wiring lines. Due to the flexibility of the CASSP modules. This can be fabricated with 3-5mm thick and 20mm wide aluminium (Alloy 1060H12) flats which would weigh just 3Kg for a 4m diameter pod.

III.II Carbon Nanotube Electron Field Emitter

Microwaves are generated by passing electrons through specially designed cavities within a magnetic field. Klystron and Magnetron tubes were invented during the 2nd World War and continue to have the highest efficiency.

Commercial high power Klystron tubes with high power ratings are manufactured by Toshiba Electron Tubes & Devices Ltd. A 2.45 GHz, 30kW continuous output Klystron under development has an efficiency of 50% and weighs 150Kg. [22] (5g/W)

The efficiency of a Microwave emitter depends on its mode of operation. They have very high efficiencies only when operated in a pulsed mode.

The most critical components of a Klystron or Magnetron amplifier is a thermionic electron emitter. This consists of a filament that is heated to over 2000K. Electrons thus generated are accelerated into a cavity by a large Voltage of several kilovolt (kV). The hot electrons rapidly heat up the Klystron tube thus requiring continuous active cooling. This is the reason for low efficiency while operating continuously.

Carbon nanotubes are the best electron field emitters known to mankind. They can sustain currents of >150A/cm^2 [23] with Voltages of just 1-2V/µm. This would make them an ideal material to make microwave emitters.[24] The cold cathodes can reduce heating problems of Microwave tubes significantly while increasing efficiency. The low heat generation would allow for lighter composites to be used to fabricate the Microwave tube cavity.

Usage of Carbon Composites in place of steel would lead to a factor of ten reduction in weight. The cold emission would reduce heating substantially and minimize cooling requirements. Assuming a factor of 5 reduction in weight and a nominal 10% increase in efficiency to 60%. The weight per Watt of energy transmitted is (1g/W).

The Carbon Nanotube field emitters currently have a TRL of 4. They have been used commercially as electron sources for portable X-Ray diffraction equipment.

MICROWAVE PROPULSION

NASA-CANNAE recently published a research paper claiming that Microwaves could be used for propulsion when injected in specially designed cavities[25]. This is known as the CANNAE drive. Lab tests claim that the system works but with a very tiny force. If this system is proven to work as claimed by the inventors. We could use off-peak energy produced by the SPS for Orbital corrections

Module	SPS-ALPHA	CASSP
HexBus	~25Kg	~3Kg
Solar Power Generation Module	15-20Kg	~3Kg
Interconnects	~1Kg	~1Kg
Reflector & Structural Beam	~125-150Kg	-NA-
Wireless Power Transmission Module	~50Kg	~10Kg
Propulsion Control Module	50-500Kg	10-100Kg
TRL	3	3

Table 2: Comparison of Module weights of SPS-ALPHA and CASSP Satellites.

IV. ECONOMIC VIABILITY OF CASSP

A 2007 study, "Space-based solar power as an opportunity for strategic security" by the Pentagon's National Security Space Office pointed out that Space based Solar power would be viable as a strategic power source in inaccessible areas such as islands or battle fields where the cost of power is ~$1-10/ Unit as against a few cents on mainland[26]. Continuing in this line of thought. The first target customer for CASSP would be an island located close to the equator with huge potential for economic growth. One such island is the Andaman & Nicobar Islands of India. These islands are strategically located between mainland India, Singapore, Australia, Malaysia and Thailand. It has a huge potential to be a major trading hub but is held back due to lack of any energy resource.

Almost all the energy on the islands is produced by burning diesel and wood.[27] This would be a perfect test bed for deploying space solar power. The cost of energy generation on these islands is between US$0.5-US$1/Unit and is directly subsidized by the Government of India.

The current installed capacity of the islands is 35MW and this can barely meet the energy requirements for lighting. The annual energy consumption in kilowatt-hours is 306 million units. The Annual energy bill is ~US$153-306 million USD.

Assuming a 50MW initial CASSP satellite to meet the energy requirements on the island. The potential energy consumption is 438 million units. The potential revenues per annum are US$219-438 million.

From Table 1. The cost of SWCNT based Solar panels for generating 50MW of energy is USD 5 million.

Each CASSP module is capable of delivering 6.3kW. Due to losses in microwave conversion. We must produce 40% more power than what is received on earth. So this system would require ~11200 solar generator modules weighing 33.6 metric Tons.

From the previous discussion on Carbon nanotube field emitters. A Carbon nanotube powered Klystron would weigh 1/5th of a commercial source at 1g/W of energy radiated. A 50MW Klystron would weigh 50 metric Tons. A magnetron producing 2kW costs ~US$50. Assuming a 5-10x cost increase for Klystron. This would cost ~USD125-250 per kW of energy transmitted. The Klystron Amplifier would cost ~12.5 million USD.

Interconnects, propellant, micro-robots etc…are expected to weigh an additional 30 metric Tons. This brings the total satellite weight to around 113.6 metric Tons.

Ground systems are expected to cost ~US$50 million. They would be deployed in small diverse clusters in order to meet energy needs of each individual island.

The system would be launched abroad an emerging Heavy lift launcher such as SpaceX Falcon Heavy which is expected to launch in 2015[28]. From various estimates, a single launch on SpaceX heavy would cost US$135 million. The total launch cost is therefore US$270 million.

Thus the total cost for deploying CASSP is US$337.5 Million. With expected revenues in the range of US$219 – 438 million. CASSP can pay for itself within 2 years of operation.

SPIN-OFF REVENUE SOURCES

A CASSP satellite would be located in the geosynchronous orbit. It would already have a powerful microwave transmitter to beam energy. By adding additional signal processing hardware, the satellite could be used as a powerful communication satellite with minimal additional cost. A communication satellite with a 25kW rated power costs about $300million to build and launch. An SPS satellite could relay these communication signals along with power transmission by piggybacking on the main signal. This would provide a dual use of both data and power further enhancing the value of the satellite. A CASSP satellite with a communication satellite module could generate annual revenues of more than US$120Million.[29]

V.CONCLUSION

A space solar power satellite is more realistic than ever due to the emergence of Carbon nanotechnology. A satellite can be built, launched and made economically viable using technologies that have just begun emerging from laboratories. The most feasible deployment of SPS would be on an island with a large growth potential. Further work is required to make more accurate estimates and take the technology from lab to actual deployment in space and then to its logical end as the clean energy source to power our future.

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