Efficiency Calculation of Space-Based Solar Power Generation

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Abstract—In the 21st century energy demand is increasing day by day to overcome this energy need Space-Based Solar Power generation proposed a new technique to fulfill the increasing energy demand. It has high efficiency as compared to the earth-based solar power generation. In this technique, we will establish satellite constellation at the geosynchronous earth orbit "GEO,". At this constellation solar panel architecture is attached, which capture energy from the sun at GEO orbit where solar energy will not face any hindrance as in earth-based solar power generation "EBSP,". For instance, in EBSP maximum energy will not reach to the earth due to atmospheric attenuation, weather condition. Moreover, in SBSP, it will not face any such type of hurdle and at GEO, 30% maximum solar energy is present. When solar energy is captured by the satellite constellation plus solar panels assembly, it will be transmitted to the earth with the help of Wireless Power Transmission "WPT," technique. In this paper, we will be concentrating mainly on the estimation of mathematical efficiencies of both approaches for power generation .i.e. space-based solar power generation "SBSP," and EBSP. At the end of this paper, all mathematical calculation reveals that proposed idea for power generation which is SBSP has more potential as compared to the EBSP.

Index terms: space-based solar power generation, Earth-based solar power Generation, Renewable resources Non-renewable resources, Rectenna, SBSP efficiency, EBSP efficiency

I. INTRODUCTION.

Electrical Power is required to run the industrial and household loads. During the 20th century, the main increase in energy consumption was about 16 folds and the forecast shows that the future energy consumption increases up to 25-fold in the next 50 years. The issue, like global warming, raises carbon –dioxide emission all these facts that threaten the existence on the mother planet. i.e. Earth [1]. In Pakistan, two types of energy resources are current Non-Renewable energy resources Renewable energy resources.

All fossil fuels, nuclear energy resources fall into this classification. But Non-Renewable energy resources have become hinder the use as a factor of primary power sources due to some disadvantages such as Non-renewable energy resources are limited once they finished they can't be replaced. Nonrenewable energy resources have a negative impact on the environment in processed and consumed like CO_2 emission they also have high health risks, like uranium used in nuclear power plant cause adverse birth effect, abnormal heart diseases. Unsustainable energy reserve is conserved they become more and more expensive as they are used [2]. Even we have more non-renewable energy resources but due to its limited quantity and negative impact on the environment, we have to look alternate energy resources. So in conclusion and with respect to all the disadvantages of this type of energy resources, renewable energy resources are better . Renewable energy resources are those that recover naturally.

For example, solar energy, tidal energy, hydroelectric power energy, wind energy, biomass energy, geothermal energy. The different renewable resources are the main source of energy. These resources are also called clean and green as a number of emissions are relative. The advantage of this type of energy is its sustainability, they require less maintenance and their fuel is provided from the natural resources which reduced cost. They produce no waste product so they don't have a negative impact on the environment. So, for the energy production we should adopt renewable energy and among all the renewable energy resources sun is a readily available resource. The conventional manner of using solar energy is one to collect the radiation emitted by a sun and turn it into Electricity into usable form via a solar collector or solar concentrator. Virtually 355 days are sunny days in the Pakistan throughout the year and due to the equator temperature, it will be high so we will get more solar energy as compared to all the renewable energy resources. Sun is the most enormous and cheap sources of energy among all renewable energy resources. In order to store this energy solar cells (photovoltaic cells) are used and therefore the name Solar photovoltaic. Sun has high theoretical potential as compared to all the renewable energy resources Energy comparison of Solar with the other renewable energy resources.

TABLE I

ENERGY COMPARISON OF SOLAR WITH OTHER ENERGY RESOURCES [8]

Energy Resources	World			
	Theoretical Potential (TW)	Extractable Potential (TW_c)	Technical Potential (TW_c)	2001 Supply (TW_c)
Hydropower	12 TW	3.5[18]	1.2[19]	0.23[30]
Ocean Wave	34 TW	8.5[23]	0.62[24]	~ 0[25]
Ocean Surface Currents	8.1 TW	2.0[28]	0.012[29]	~ 0
Ocean Thermal Gradient	3.9 TW	0.033[31]	0.0033[33]	~ 0[33]
Ocean Salinity Gradient	3.0 TW	0.74[36]	0.074[37]	~ 0
Ocean Tidal	2.4 TW	0.60[39]	0.037[40]	0.000050[41]
Wind	1,000 TW	250[43]	14[44]	0.0050[45]
Geothermal	44 TW	2.8[48]	1.9[49]	0.0050[50]
Solar Electricity	89,000 TW	58,000[53]	7,500[54]	0.00015[55]
Solar Fuels	89,000 TW	67,000[58]	2,500[59]	0.19[60]
Solar Thermal	89,000 TW	19,000[47]	5,600[64]	0.00060[65]

The solar insolation (the amount of solar energy coming to the earth) is 1.37, but the surface area of the earth over which this flux is averaged over time is 4πr2 where r is the radius of the earth (r=6378.1Km)Therefore the incoming solar intensity to the ground atmosphere is

$$(1.37kW/m^2)/4 = 342.5W/m^2 \quad (1)$$

When reached this radiation at earth it will face atmospheric attenuation, approximately 30 % of this solar flux scattered, clouds and atmosphere absorbed 19%.Therefore the overall average solar intensity that reaches to the earth is

$$342.5W/m^2.(1-0.49) = 174.7W/m^2 \quad (2)$$

The hypothetical capability of sun based force is the integral of this normal flux over the world's surface range

$$P = (174.7W/m^2).(4\pi r^2) \quad (3)$$

$$= (174.7W/m^2).4\pi r^2.(6378km)^2 .(10^6 m^2/km^2).(10^{12} TW/W) = 89300TW \quad (4)$$

So this much measure of hypothetical potential we can get from the sun at the earth surface. In Pakistan we have more sunny days and nearest to the equator .so solar energy is best suitable energy resources for this country among all the renewable energy resources.

Table I reveals theoretical potential, the extractable potential of all renewable energy resources in which solar electricity, solar fuel, and solar thermal has the highest potential among all of these renewable energy resources.

But, in solar energy we have two possibilities of energy production techniques from the sun:

1. Earth-Based Solar Power System "EBSP."
2. Space-Based Solar Power System "SBSP."

GENERIC FUNCTIONAL ARCHITECTURE OF SPACE-BASED SOLAR POWER SYSTEM

In this section, SBSP infrastructure will be discussed. With a particular deciding objective to evaluate and examine the distinctive SBPS methodologies as mentioned in [3] it was essential to make sense of whether there are general utilitarian segments that depict the greater part of these. Fortunately, this was actually the case Figure 1 reveals that whole infrastructure of SBSP

- SBPS Platform
- Ground Platform
- Supporting Systems/ Infrastructure

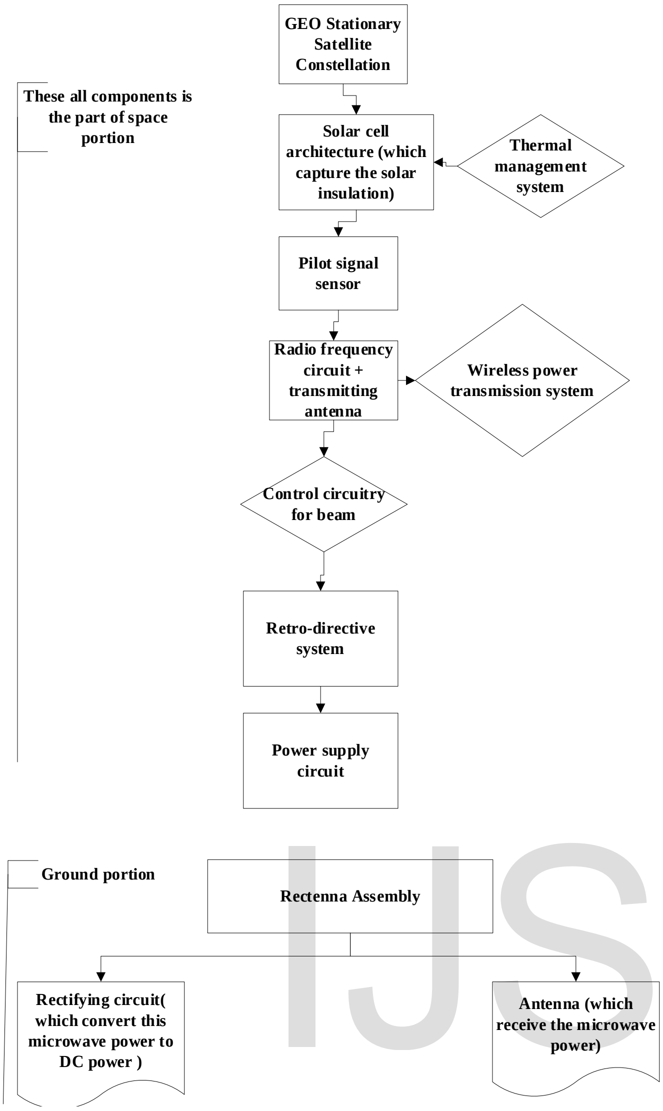

Fig. 1. *SBSP infrastructure*

Space Portion infrastructure

This portion mainly consists of several sub-portion (1) solar cell (2) radio frequency circuit transmitting antenna (3) pilot signal sensor (4) control circuit for beam (5) retro directive system (6) power supply circuit.

Ground Portion infrastructure

This portion consists of only Rectenna assembly which receives the microwave power and then converted to DC form Rectenna actually consists of rectifying circuit and antenna. An antenna which receives the microwave power and rectifying circuit which converts this microwave power to DC power.

Comparative study of SBSP with EBSP

This section tells us that, which system is better for power generation and why we are adopting the system. This comparison is made on the basis of end to end efficiency of SBSP system that established in the geosynchronous earth orbit "GEO," stationary earth orbit with the EBSP by considering solar constant on average is 1367 W/m2 (astronomical unit) and considering the efficiency of each system and all losses in transmission and then converted into the electrical power.

Space-Based Solar Power Approach

The SBSP concept was invented by Peter Glaser and Arthur D. Little in their feasibility report. The more detailed examination was done by both NASA and the Department of Energy "DOE," in a number including the 1980 Satellite Power System Concept implementation and Evaluation Program of Assessment Report." [3]. Fig 2 reveals the whole idea of SBSP reference concept. It is designed for a 5-GW framework with an extensive 50-km^2 solar based cell exhibit (5 Km in width and 10 Km in length) that is placed in GEO that changes over daylight to electrical energy and more close to the sunlight, now this huge amount of energy is transmitted to the earth with the help of microwave antenna which is 1Km diameter antenna. The high-frequency microwaves are collected on the earth surface at Rectenna assembly which is 10 km in diameter and half wave dipole antenna that change into electrical energy after which given as an input to the grid system.

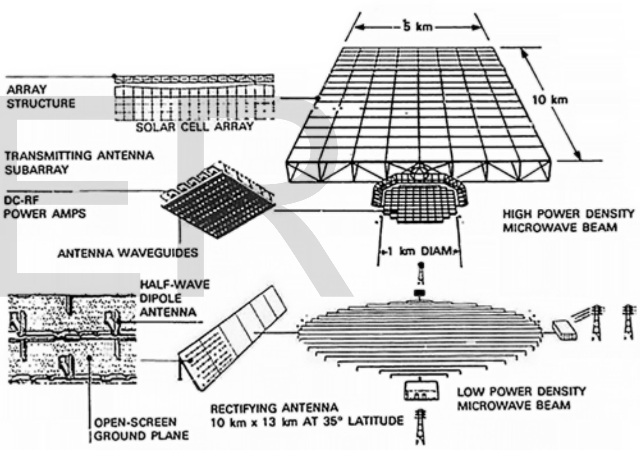

Fig. 2. *Assembly of space-based solar power project* [8]

By utilizing the reference idea as a beginning step, a general investigation is being conducted to explore the overall proficiency of a 1-GW (gigawatt) SBSP.

Now to get the total estimation of overall accomplishment of SBSP first calculate the efficiency of each and every step

Technical Steps

1. Photovoltaic conversion to DC,
2. Power monocrystalline and distribution efficiency
3. DC to RF conversion efficiency
4. Accommodation of scan losses which is phased by microwave antenna
5. Atmospheric damping to microwave transmission
6. RF efficiency of the collection space
7. Radiofrequency "RF," to direct current "DC," conversion
8. Direct current to alternating current conversion efficiency
9. Power monocrystalline and distribution efficiency.

A. Mathematical Calculation of efficiency of SBPS

On the average solar constant, (solar irradiance) incoming energy from the sun is 1367(W/m2).and the SBSP assembly is currently in the space so it will not face any hurdle like weather, atmospheric attenuation, and day/night cycle .in general Photovoltaic conversion to DC efficiency is 30%

$$1367(W/m^2)*30/100 = 410.100(W/m^2) \tag{5}$$

The next is power monocrystalline and distribution efficiency is 99% and we have the remaining power density is 410.100 W/m2

$$410.100(W/m^2)*99/100 = 405.99(W/m^2) \tag{6}$$

Next is DC to RF conversion efficiency is 85% and the remaining power density is 405.999(W/m2).

$$405.999(W/m^2)\cdot 95/100 = 345.09915(W/m^2) \tag{7}$$

After this the energy is converted into the microwave radio frequency wave .i.e. 345.099W/m2

And microwave antenna phase scan losses is 90%

$$345.099(W/m^2)\cdot 90/100 = 310.589(W/m^2) \tag{8}$$

And this microwave energy is transmitted to the earth so some losses occur in the atmosphere; therefore Atmospheric attenuation to microwave transmission is 90%

$$310.589(W/m^2)\cdot 90/100 = 279.53010(W/m^2) \tag{9}$$

279.53010 (W/m2) energy is reached into the earth and at earth, this energy is collected at the receiving antenna .i.e. Rectenna so in general RF collecting area efficiency is 90%

$$279.53010(W/m^2)\cdot 90/100 = 251.57709(W/m^2) \tag{10}$$

251.57709(W/m2) energy is at the Rectenna this receiving antenna convert this energy into the DC so, efficiency of RF to DC conversion by Rectenna is 90%

$$251.57709(W/m^2)\cdot 90/100 = 226.41938(W/m^2) \tag{11}$$

Now energy is currently in the DC format the Rectenna output this DC is converted into the AC form and in general DC –AC conversion efficiency is 94%

$$226.41938(W/m^2)\cdot 94/100 = 212.83422(W/m^2) \tag{12}$$

And at the earth power monocrystalline and distribution efficiency is 95% so total power density at the end is

$$212.83422(W/m^2)\cdot 95/100 = 202.19251(W/m^2) \tag{13}$$

So total power density is (202.19251) W/m2 . Table II gives the whole summary of the above calculation.

TABLE II
SPS Efficiency Calculation [6]

Segment	Efficiency	Power (W/m^2)	Notes
Sunlight	100%	1367	Maximum on a flat panel in space
Photovoltaic conversion to DC	30%	410	Best predicted solar efficiency
Power management and distribution	99%	406	
DC to RF conversion	85%	345	
Microwave antenna phase scan losses	90%	311	
Atmospheric attenuation to microwave transmission	90%	280	
RF collection area efficiency	90%	252	
RF to DC conversion	90%	226	
DC to AC conversion	94%	213	Supplies electricity to grid frequency
Power management and distribution	95%	202	
Total end-to-end efficiency	14.79%	202	Best Predicted

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B. Earth-Based Solar Power System

In the earth based solar power system, the first question comes in our mind is that how many photons (packets of energy) reach to the earth surfaces? This figure given below shows the whole idea of incoming solar radiation.

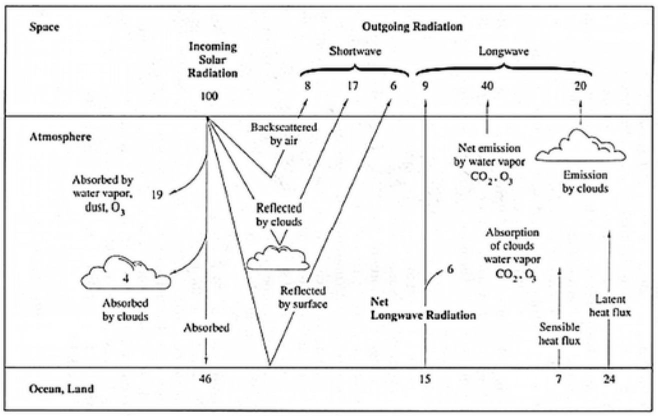

Fig. 3. *Incoming solar insulation at the earth*

The primary parts in this outline are the as follow

Radiation from the Sun that achieves the highest point of the air is of optical wavelength.

Clouds mirror 17% once again into space. In the event that the earth gets more over cloudy, as some atmosphere models anticipate, more radiation will be reflected back and less will achieve the surface.

8% is scattered in reverse via air atoms:

6% is specifically reflected off the surface again into space So the aggregate reflectivity of the earth is 31%. This is actually known as an "Albedo". Presently What Happens to the 69% of the approaching radiation that doesn't get reflected back:

- 19% gets retained specifically by dust, ozone and water vapor in the upper environment
- 4% gets consumed by mists situated in the troposphere.
- The staying 43% of the daylight that is on top of the world's air achieves.

Now we know how many percentages of sunlight comes at the earth surfaces and we are able to calculate the end to end proficiency of earth-based solar power system. By comparison, a Concentrated Solar Power "CSP," tower design is being investigated. The Fig.4 given below describes the concept as a series of solar modules that capture sunlight on a receiver on top of a central tower.

All the heat energy would be converted into the salt solution with the help of receiver and then this solution is stored in storage tanks. This system is adopted because among all the earth based solar power system this has higher efficiency. This procedure has numerous similarities to the ordinary atomic system, oil, gas, and coal- steam power plants.

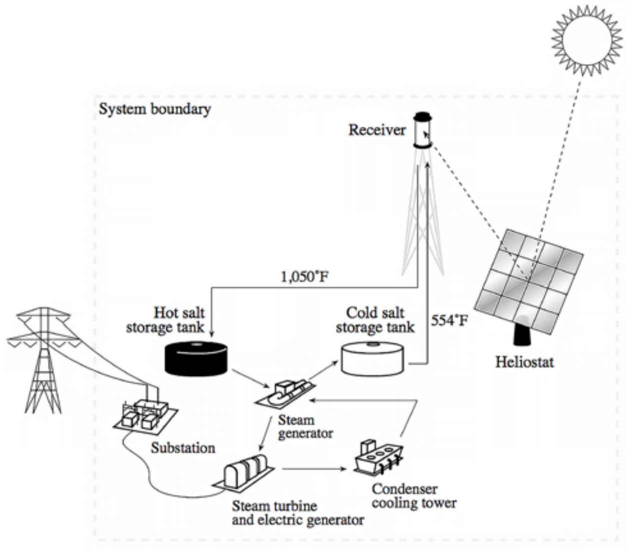

Fig. 4. *Architecture of Concentrated solar power system*

Mathematical Calculation of effeciency of earth-based solar power system

The average solar constant is 1367 W/m2 atmospheric attenuation as discussed above is 69% so the radiation will be

$$1367(W/m^2)*69/100 = 943.2300$$

(14)

69% remaining solar radiation that is not reflected back is absorbed by weather and dust particle

So the annual weather, water "H2O," , hourly & dust corrected irradiance is 60%

$$943.2300(W/m^2)\cdot 60/100 = 565.93800(W/m^2)$$

(15)

The remaining sunlight efficiency is 43 % at the day /night cycle

$$565.93800(W/m^2)\cdot 43/100 = 243.35554(W/m^2)$$

(16)

But here is also a method to increase the power density with the help of dual axis tracking system and in general its efficiency is 136%.

$$243.35554(W/m^2)*136/100 = 330.96334(W/m^2)$$

(17)

It is better than the flat panel, now this energy is current at the power tower and in general power tower configuration efficiency is 14%

$$303.96334(W/m^2)\cdot 14/100 = 46.33487(W/m^2)$$

(18)

This is the power density at the power station and this is capable to generate the energy in the night so the night generation efficiency from thermal energy storage system is 150 %

$$46.33487(W/m^2)\cdot 150/100 = 69.50230(W/m^2)$$

(19)

And as given in above table power monocrystalline and distribution efficiency is 95%.

$$69.50230(W/m^2)\cdot 95/100 = 66.02719(W/m^2)$$

(20)

So at the end, total power density in the earth-based solar power system is 66.02719W/m2 which is very less than the space-based solar power system so this indicates SBPS system is better than the EBSP.

TABLE III

CALCULATION OF EFFICIENCY OF EARTH BASED SOLAR POWER [6]

Segment	Efficiency	Power (W/m^2)	Notes
Sunlight	100%	1367	Maximum on a flat panel in space
Atmospheric attenuation to sunlight	69%	943	Maximum for desert regions
Annual weather, H_2O, hourly, & dust corrected irradiance	60%	566	Average daily direct on a flat panel in Phoenix, AZ
Daylight cycle	43%	243	Phoenix latitude is ~ 245 W/m^2 average
2-axis tracing	136%	331	Better than a flat panel; keeping incidence angle normal
Power Tower configuration	14%	46	14% is current efficiency rating
Night generation from thermal energy storage	150%	70	Heat storage in salt medium generates power at night
Power management and distribution	95%	66	
Total end-to-end efficiency	4.83%	66	Agrees with NREL efficiency predictions

So the above calculation shows that the SBSP has higher efficiency as compared to the EBSP.

TABLE IV

Sources of Inefficiency	Efficiency	Power (GW)	Notes
Input power (GW dc)		2.672 dc	
RF Circuit Efficiency			
DC to RF converter efficiency	0.860	2.298	Assumes average converter efficiency
RF filter insertion loss (IL)	0.891	2.048	Estimated total IL=0.5dB
Transmitting Antenna Efficiency			
Subarray random electronic failures	0.960	1.966	Estimated 2% failures
Meteorite hit element failures	1.000	1.966	100 failures / year
Amplitude error	0.996	1.957	±1dB amplitude deviation
Phase error	0.978	1.914	±15° phase deviation
Phase quantization	0.997	1.908	5-b phase shifter
Taper Quantization	0.989	1.886	10 steps
Antenna aperture efficiency	0.980	1.849	Conductive losses in aperture
Transmitter scan loss	1.000	1.849	Assumes broadside radiation
Mismatch loss	1.000	1.849	Assumes Array VSWR= 1.0
Beam Coupling Efficiency			
Propagation loss	0.979	1.809	Rain rate = 4 mm/hr @ 5.8GHz
Collective efficiency	0.921	1.666	Gaussian beam taper = 10.14 dB
Polarization loss	1.000	1.666	Assumes near perfect alignment

Rectenna Efficiency			
Rectenna random failure	0.990	1.646	Estimated 1% failures
RF filter insertion loss (IL)	0.891	1.469	Estimated IL = 0.5 dB
Rectenna scan loss	1.000	1.469	Rectenna tilted to avoid loss
Mismatch loss	1.000	1.469	Assumes Array VSWR = 1.0
Rectenna efficiency	0.850	1.263 dc	Projected optimized efficiency
DC to utility grid efficiency	0.950	1.200 dc	Assumed dc-dc converter efficiency
System dc-dc efficiency	45%		

TABLE IV

CONCLUSION

In this paper, research has been done on the two technical approaches for the energy production. .i.e. EBSP, and SBSP Energy comparison of the sun with the other renewable energy resources and Space-based solar power system infrastructure has been discussed. In comparative study of SBSP and EBSP , space-based solar power has more power density .i.e. (202.19251) W/m2 as compared to the earth-based solar power .i.e.(66.02719)W/m2 .And these power densities are verified from the Table [II] and Table [III]. By seeing all the mathematical calculation results of SBSP and EBSP it is suggested to adopt a new approach for the energy production which is SBSP.

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