Cost Minimization Strategy for Satellite Solar Power Station

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Abstract The space-based solar power system for the baseload power supply on the ground is more than science fiction now, and it will be practical in the coming future. Due to its high estimated space launching cost, it was suspended in earlier attempts. With Technological advancements and research going on worldwide, its practical implementation could be possible by 2030. This work is motivated in a direction to reduce total system cost. The economic model of the system has interrelated parameters which can be optimized for the high efficiency and cost-effective performance. In this work, a cost minimization method is derived, and results are investigated for economically efficient space-based solar power prototype design. The Derived generalized mathematical Expressions are appropriate to evaluate the cost-effectiveness and performance of the microwave-based wireless power transfer system. The effect of transmitting antenna size is investigated for the desired power density on the receiving ground antenna. The Levelized cost of energy (LCOE) is also calculated for the space-based solar system; it can be easily yielded from the generalized cost expression.

Keywords- Energy; Green energy; Renewable energy; solar energy.

1. Introduction

Sun is the source of clean and endless energy [1]. The solar energy received on Earth every hour is nearly two times the annual energy expense of Humankind [2]. Solar Photovoltaic converts solar energy into electricity, but it needs regular care and maintenance [2], [3]. Solar thermal is another way to utilize solar energy available on the earth [4], [5]. But for terrestrial use Sun irradiance fades away on cloudy and stormy days, and obviously, it is not present at night [6], [7]. On the other hand, among the accessible renewable energy resources, space-based solar energy is most desirable as it can provide 24-hour clean energy [8]. Over the earth based solar system, the Satellite solar power station (SSPS) has added threefold increases in power accessibility [9]. Therefore it is appropriate as novel energy structure that can promote sustainable headway of humankind. SSPS implementation fundamentally relies on the microwave production and transmission systems. Therefore, it requires microwave technology innovations on a large scale [10]. In a satellite solar power station, as shown in "Fig.1", space satellite collects sun irradiance and photovoltaic transform it into electrical energy. This electrical power is changed into the microwave and transmitted remotely to receiving antenna on Earth. The receiving antenna associated rectifiers changes microwave power back to electrical power [10]. This way, the space energy is available on the earth to supply in the commercial grid after appropriate power processing [11].

In SSPS, Wireless power transfer from space to the ground receiver is performed using microwave transmission, shown in "Fig.2". For the SSPS design or practical implementation, an optimization technique is required that considers system tradeoffs in critical components parameters [3]. The key is the selection of high conversion efficiency and cost-effective components for (a) solar to microwave conversion, (b) microwave to electrical power conversion at receiving site on the ground, and (c) technology with low transmission losses due to attenuation, diffraction, and scattering [3]. Transmitter size and mass is an important parameter as it will decide space launch cost. There are also safety and environmental issues

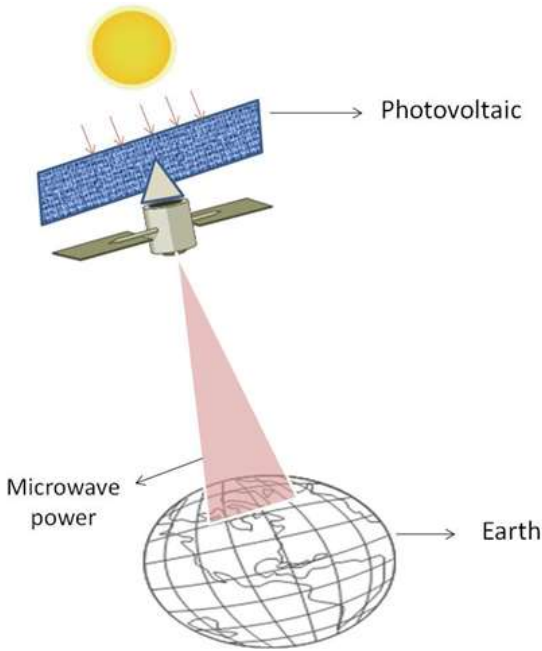that must be considered, i.e., 100 mW/ cm^2 microwave radiation [12].

Fig.1. Space solar power [13]

Here transmission at higher microwave frequency is advantageous; it will reduce transmitter and receiver size of the system. However a SSPS design requires transmitting antenna phase array structure that is capable of producing a Gaussian beam [3], thus at a higher frequency, the individual components will become very small and practically impossible for manual fitting or manufacturing [9]. In future, more advancement in robotics for the purpose may support phased array manufacturing at higher frequencies. For now, system frequency at 2.45 GHz and 5.8 GHz is considered; these frequencies are in the atmospheric window [9].

This work proposes a cost minimization approach for SSPS design. In Space section, transmitting antenna size lessening is possible utilizing optimized interrelated parameters of the system components. For this purpose, generalized Mathematical expression of SSPS economic model is derived. Further Transmitting antenna size and associated received power that satisfies the least cost condition is evaluated. The generalized model considers Gaussian beam microwave transfer for large distance high power transmission. Parameters selection for the minimum cost is derived, the derived model is suitable for cost-effective SSPS deployment. SSPS Levelized cost of energy is evaluated by including components life cycle cost and space launch cost at the initial stage.
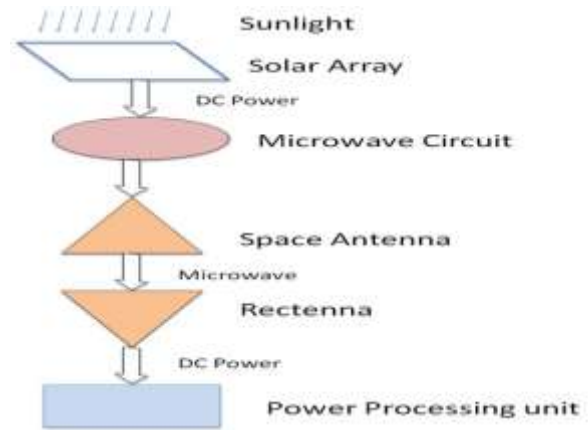

Fig.2. Satellite solar power station diagram

2. Wireless Power Transfer via Microwave

In the wireless power transmission (point to point), highly directive transmitting and receiving antenna is required [3]. The phased array antenna beamforming technique is a mature technology nowadays [3]. It is used for the design of high directive beam; "Fig.3" shows the propagation of the beam. Here it can be observed, the traveling wave behave as linear wavefronts for the main lobe region, and thereafter it starts propagating like spherical wavefronts [8]. The main lobe length (planar wavefronts) is called near-field region and beyond this (spherical wavefronts) is called far-field region [11]. Since each propagating wavefronts is a packet of the same power, power density depends on the wavefronts own surface area, i.e., more surface area results in less power density at a point. Therefore in wireless power transfer, a receiving antenna beyond the main lobe is undesirable. SSPS consider very large distance microwave power transmission, i.e., from GEO orbit to earth (36000 km). Therefore a propagation technique is required that covers such large distance under main lobe region. Otherwise, power density received on the earth surface will be too low and rectenna size required to receive most of the power will be very large and impractical [14]. In general, Friis transform equation [15], which is used in the communication is given in equation (1); it is called far field condition friis transmission. It is noted that (1) is not valid for SSPS power transfer because SSPS considers near field condition [15].

$$\frac{p_{recieved}}{p_{transmitted}} = G_t G_r \left(\frac{\lambda}{4\pi D}\right)^2 \tag{1}$$

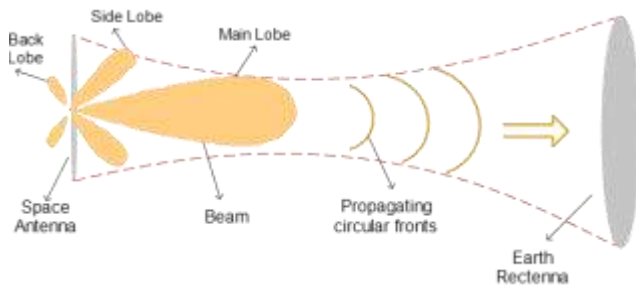Where G_t and G_r are the antenna gains, λ is the wavelength

Fig.3. Directive beam propagation [15]

2.1. High power transmission for large distance

SSPS aims for sending high power wirelessly for the large distance, i.e., from geostationary equatorial orbit (GEO) orbit to earth (36000 km) [16]. To make SSPS in the near-field region is a challenging task, but with technology advancement it is possible.

The most suitable way for near-field region SSPS design is using Gaussian beamforming for the transmission [3], [9]. A properly designed phase antenna array with amplitude tapering is utilized for Gaussian beamforming. Gaussian beam generates planar wavefronts for a high range of distance, so it is suitable for SSPS implementation [17]. Wave propagation using Gaussian wavefront is shown in "Fig.4". For the Gaussian beam propagation, Rayleigh length is the boundary condition, where linear wavefront changes to circular. So the distance up to Rayleigh length is called near field condition and beyond this is called Far field condition [15]. For the efficient point to point power transfer, the receiver antenna must be placed within near field condition. Equation (3) gives expression of Rayleigh length; it depends on the beam waist ω_0 at the transmission level [15]. A proper tapered phase antenna can be designed with large beam waist such that it covers GEO distance within near field condition.

The power density received on the ground rectenna is also a key issue. Considering SSPS in Rayleigh length or near field condition. In this case, the Gaussian beam reaches ground antenna; the average power density P_d depends on Beam waist contour ω (z) and Radius of curvature R (z), where z is the distance from transmission level [3]. There are safety and security limits on microwave power density level on the ground, which needs critical consideration in design procedure. Also, it has to be noticed; the designed rectenna efficiency is sensitive for variation in P_d, for a fixed P_d value maximum efficiency obtained. Therefore SPPS design depends on many interrelated parameters and an optimized design is required. Here parameters Z_0, ω (z), R (Z) are given as follows.

Beam waist contour
$$\omega^2(z) = \omega_0{}^2\left[1+\left(\frac{z}{Z_0}\right)^2\right] \quad (4)$$

Radius of curvature
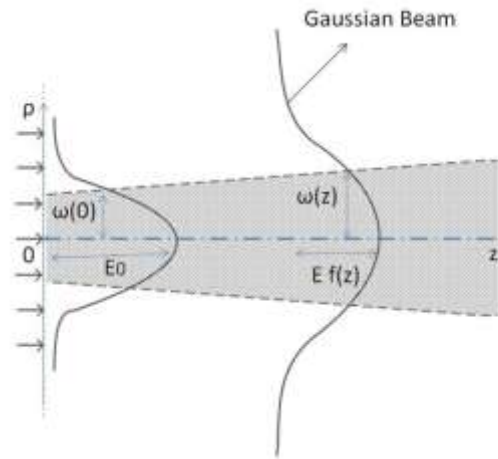$$R(z) = z\left[1+\left(\frac{Z_0}{z}\right)^2\right] \quad (5)$$

Fig.4. Gaussian beam propagation [15]

$$\frac{p_r}{p_t} = \frac{\left|\int_A E_r\, \cdot E_t\, ds\right|^2}{\left\{\mathrm{Re}\int_{A_r}|E_r|^2\, ds\right\}\left\{\mathrm{Re}\int_{A_t}|E_t|^2\, ds\right\}} \quad (6)$$

Here, P_r, E_r, power and electric field at Receiving station respectively;
P_t, E_t, power and electric field at transmitting station respectively
A_t, Transmitting antenna area
A_r, Receiving antenna area

$$\frac{p_r}{p_t} = \frac{A_t A_r}{\left(\frac{A_t+A_r}{2}+\lambda^2 D^2\right)} \quad (7)$$

λ, Operating wavelength

D, distance between

Rayleigh length
$$Z_0 = \frac{\pi n \omega_0}{\lambda} \quad (3)$$

$$\frac{p_r}{p_t} \; ; \; \frac{A_t A_r}{\left(\lambda^2 D^2\right)} = \tau^2 \qquad \tau^2 \text{ is power} \tag{8}$$

transmission efficiency

$$\eta_{beam} = 1 - e^{-\tau^2} \qquad \text{Beam efficiency} \tag{9}$$

Considering near field condition, transformed Friis transmission equation is given in (8) [15].

3. SSPS Estimated Economic Modeling

This work is cost estimation assessment for SSPS introductory cost concerning interrelated parameters of the components. Initial expenses are characterized as follows:

$Initial\ cost = solar\ array\ cost$
$\qquad + microwave\ circuit\ cost$
$\qquad + transmission\ antenna\ cost$
$\qquad + recieving\ antenna\ cost$
$\qquad + power\ prrocessing\ unit\ cost$

The space section introductory costs comprise of the solar array cost, microwave equipment cost, and microwave transmission cost [14]. The microwave power beam exchanges the space energy to the earth. The ground rectenna then changes over the received microwave power back to electrical energy. In the ground, segment cost is expected as the cost of rectenna and power handling unit [9], [14]. The above expression terms could be expressed mathematically in the form of interrelated parameters as given below:

$$C = \frac{m_s P_t}{\eta_{sm}} + m_t P_t + a_t A_t + m_r P_r + a_r A_r \tag{10}$$

Here, C = Initial cost; P_t = Transmitted power; m_s = Cost of Photovoltaic power per KW; η_{sm} = Photovoltaic conversion efficiency; m_t = Cost of equipment to convert microwave power per KW; a_t = Cost of transmission antenna per unit area; A_t = Transmission antenna area; m_r = Cost of ground equipment to convert received power per KW; P_r = Power received on rectenna; a_r = Cost of ground rectenna per unit area; A_r = Rectenna area.

In the formation of equation (10), it is assumed that there is a comparable model structure which has previously attained the standard cost level target [9], [14]. For the space segment, the solar array and the transmitting modules which contain both antenna and microwave power elements are taken in consideration. The solar array cost can be expressed in terms of microwave power P_t with the solar to microwave power conversion efficiency [9]. Microwave transmission cost is dependent on the components size and their power rating. For the power transmission, the related cost is linearly dependent on antenna dimension [9], [14], [18]. And the cost regarding the power ratings are also corresponding directly to the transmitted value of power (P_t) [14]. In the same way, the derivation is done for the ground segment where rectenna area

and power modules cost are formulated. The proportionality constants m_s, m_t, m_r and a_t, a_r are used in the algebraic formulation of power and area related expression in equation (1). Now, P_t can be expressed in the form of P_d (the power density at the ground rectenna site) utilizing reformed Friss equation (8).

On putting equation (8) in the Equation (10), Equation (11) and (12) gives the expression in terms of P_d. The received power density P_d is known value because it has limitation due to microwave safety and security confines. In equations (13)-(15), parameters are arranged to make expression simple.

$$C = m_s \frac{P_r \lambda^2 D^2}{\eta_{sm} A_t A_r} + m_t \frac{P_r \lambda^2 D^2}{A_t A_r} + a_t A_t + m_r A_r + a_r P_r \tag{11}$$

$$C = m_s \frac{P_d \lambda^2 D^2}{\eta_{sm} A_t} + m_t \frac{P_d \lambda^2 D^2}{A_t} + a_t A_t + m_r A_r + a_r P_r \tag{12}$$

$$C = \left(\frac{m_s}{\eta_{sm}} + m_t\right) \frac{P_d \lambda^2 D^2}{A_t} + a_t A_t + m_r A_r + a_r P_r \tag{13}$$

$$C = \left(\frac{m_s}{\eta_{sm}} + m_t\right) \frac{P_d \lambda^2 D^2}{A_t} + a_t A_t + (m_r + a_r P_d) A_r \tag{14}$$

$$C = (m_{st}) \frac{P_d \lambda^2 D^2}{A_t} + a_t A_t + (m_{rd}) A_r \tag{15}$$

Here, $m_{st} = \frac{m_s}{\eta_{sm}} + m_t$; And $m_{rd} = m_r + a_r P_d$;

3.1. Derivation for cost minimization

Up to this point, the expression has both A_t and A_r terms. Now the beam efficiency [14] as given in equation (9) is introduced to interrelate both terms. On putting equation (8) in equation (9), A_r is expressed in term of A_t parameter as in equation (9).

$$A_r = \frac{\lambda^2 D^2 \{-ln(1 - \eta_{beam})\}}{A_t} \tag{16}$$

On Putting the value of the expression (16) in the equation (15), the formulated cost is expressed now in terms of A_t, power density P_d, wavelength λ, the separation D and the proportionality constants as in equation (17). Now expression (17) can be used to find the reception antenna area

at which it will give the least cost. The derivative condition is applied as in equation (18) to determine the minimum cost value. For minimum cost case, At_{min} as in expression (19) gives the value of the required antenna dimension. On putting equation (19) in the expression (17), the minimum cost expression is derived in equation (20) and simplified in expression (21).

$$C = (m_{st})\frac{P_d\lambda^2 D^2}{A_t} + a_t A_t + (m_{rd})\frac{\lambda^2 D^2\{-ln(1-\text{ŋ}_{beam})\}}{A_t} \quad (17)$$

$$\frac{d(C)}{dA_t} = (m_{rd})\frac{\lambda^2 D^2\{ln(1-\text{ŋ}_{beam})\}}{A_t^2} - (m_{st})\frac{P_d\lambda^2 D^2}{A_t^2} + a_t \quad (18)$$

$$A_{t\,min} = \lambda D\sqrt{\frac{(m_{st})P_d - (m_{rd})\{ln(1-\text{ŋ}_{beam})\}}{a_t}} \quad (19)$$

$$C_{min} = a_t A_{t\,min} + (m_{st})\frac{P_d\lambda^2 D^2}{A_{t\,min}} + (m_{rd})\frac{\lambda^2 D^2\{-ln(1-\text{ŋ}_{beam})\}}{A_{t\,min}} \quad (20)$$

$$C_{min} = 2\lambda D\sqrt{a_t}\sqrt{(m_{st})P_d - (m_{rd})\{ln(1-\text{ŋ}_{beam})\}} \quad (21)$$

4. SSPS Prototype Estimated Cost

Table 1: SSPS prototype parameters

Parameters	value
D(km)	36000 (Geo separation)
Frequency(GHz)	2.45 & 5.8
$m_s(\$)$	1000
$\text{ŋ}_{sm}(\%)$	70
$m_t(\$)$	1000
$m_r(\$)$	200
$a_t(\$)$	4(aluminium)
$a_r(\$)$	100
$P_d(w/m^2)$	100(microwave exposure safety limits)
$\text{ŋ}_{beam}(\%)$	90

Prototype SSPS parameters are given in 'Table 1'.On putting parameters values in the expression (20) and calculated results are shown in "Fig.5", it is noted that minimum cost value is sensitive to the operation frequency and the distance D.
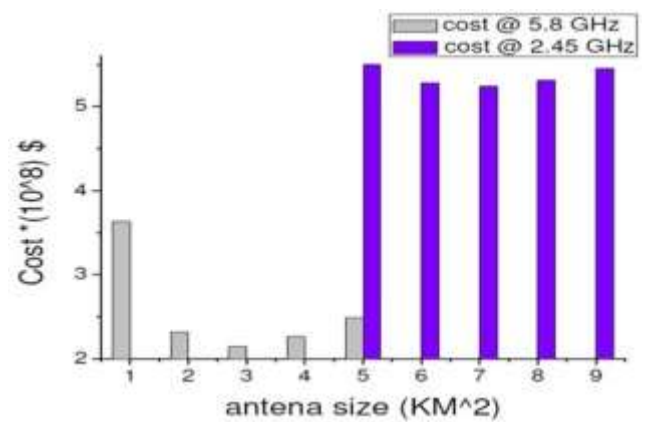

Fig.5. *Cost variation with antenna size*

4.1. Levelized cost of Energy (LCOE) estimation

SSPS life cycle of 30 years is considered. Life cycle cost includes SSPS launch cost, space segment, and ground segment. Here SSPS launch cost can be assumed 1000\$/kg in the financial year 2030 [14], [19]. For the weight to power conversion efficiency 20%, space launch cost become 5000\$/KW. LCOE for operating frequency 2.45 GHz & 5.8 GHz is shown in "Fig.6" and "Fig.7" respectively. It has illustrated here that higher variation for earlier power ratings and with increasing power it saturates.

$$LCOE = \frac{Life\ cycle\ cost}{Total\ energy}$$

4.2. Least cost per KW derivation

By using At_{min} for finding the corresponding transmitted power, received power and minimum cost per KW has found as in the equation (22), (23) and (24) respectively. Here it is noted that minimum cost per KW is independent of frequency and distance between D although the parameters P_d and ŋ_{beam} reliance are sustained.

$$P_{t_{min}} = \frac{P_d \lambda^2 D^2}{A_{t_{min}}} \tag{22}$$

$$P_{r_{min}} = \frac{P_d \lambda^2 D^2 \{-ln(1 - \eta_{beam})\}}{A_{t_{min}}} \tag{23}$$

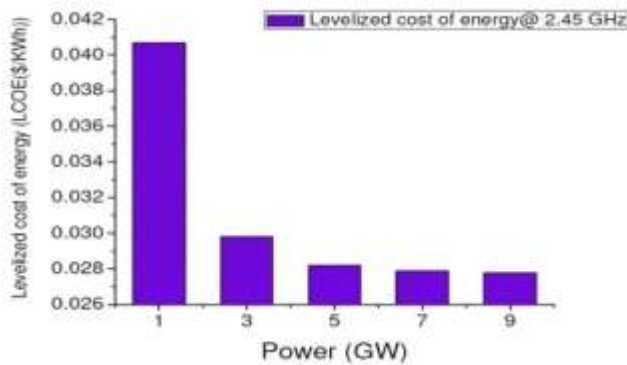$$C_{min}/_{per\ KW} = 2a_r + \frac{2m_r}{P_d} + \frac{2m_{st}}{\{-ln(1 - \eta_{beam})\}} \tag{24}$$

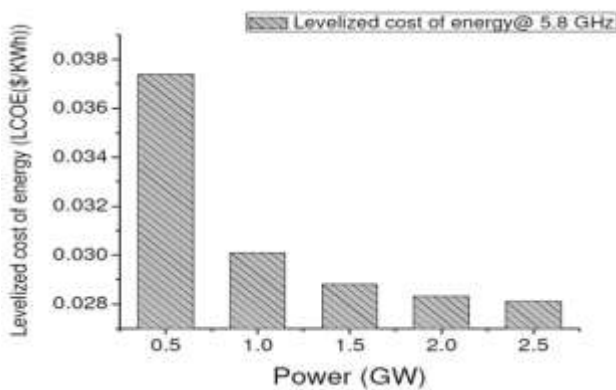**Fig.6.** *LCOE for different GW power at 2.45 GHz*

Fig.7. LCOE *for different GW power at 5.8 GHz*

5. Conclusion

This work proposes least cost derivation for SSPS framework. Efficient Microwave power transfer is essential for SSPS frameworks from a budgetary viewpoint. In Space section, transmitting antenna size reduction is possible utilizing optimized interrelated parameters of the system components. To transmit microwave power with power density (100 w/m^2) at the receiving antenna, the minimum SSPS prototype cost is derived. The minimum cost is found 5.28×10^8 \$ at 2.45 GHz and 2.3×10^8 at 5.8 GHz. In the cost vs frequency analysis, it is found to be inversely proportional. The least cost /KW value is not depending on frequency and distance because the derived power has same dependence with frequency or distance as in numerator resulting it to be

eliminated although the P_d and beam efficiency dependence is still present. The initial cost/KW with addition space launch cost/KW is determined for LCOE evaluation; the LCOE value decreases initially then saturates with power variation. At 5.8 GHz and 2.45 GHz, it saturates after 3 GW and 10 GW respectively. Therefore one can concluded, SSPS with higher capacity is economically beneficial.

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