# GROUND BASED WIRELESS AND WIRED POWER TRANSMISSION COST COMPARISON

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**Abstract**: Recent interest in applications of wireless power transmission has raised the question of the cost comparison of wireless vs wired transmission of power from ground site to ground site. Costs in terms of $/MW-km, a figure of merit, for past demonstrations and estimates for future suggested activities are given as a function of power delivery distance.

Wired power types such as open wire high voltage ac and DC lines, direct burial and submarine cables, appliance cords and circular waveguide transmission lines are discussed. Beamed RF power applications in laboratory tests, field tests, proposed direct power delivery applications and power via reflector relay are presented. Although not ground-to-ground, but ground-to-air, additional historical and proposed electric aircraft demonstrations and airship applications are also discussed for comparison.

A graph of the first approximation of installed system costs as a function of distance, in then year $ for the figure of merit is generated. Except for the very highest power, longest range cases, the wireless power cost is orders of magnitude more costly than wired power for delivery at the same distance on or near the Earth's surface.

## INTRODUCTION

Recent studies by NASA of Space (Based) Solar Power [1] have rekindled interest in transmitting electric power by RF microwave beam [2].

Those unfamiliar with the elements of costs want to find an Earth based location feature such as a canyon[3], river crossing, lake [4], strait, or other difficult crossing to apply RF wireless power transmission (WPT) thinking it must be cheaper than wired power.

To our knowledge, such a relative (albeit imprecise) cost comparison has not been published. The purpose of this paper is to attempt to document a first approximation comparison of wired and wireless RF power transmission, reception and control systems as a function of power magnitude and distance.

Because the field of WPT is rather new, we will be mostly comparing laboratory tests, first-of-a-kind demonstrations and projected application's costs with established utility costs and their long range projections. Thus, a scatter plot of these disparate costs will be used for the reader to compare, with the caveat that the various entries have markedly different provenance. Only general trends should be derived from such data.

Economical applications of beamed power in the near future will probably be for powering high altitude telecom and observation platforms, stratospheric tourism airships and other off-Earth venues. Although not strictly ground-to-ground, they are point-to-point and where data exist they will be included for comparison.

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As the two key aspects of WPT are power magnitude delivered and the distance over which it is delivered, we will use as a figure of merit (FOM) the installed system cost scaled by the distance in km and the power magnitude delivered in MW. The WPT installed costs will include the electric power conditioning at both ends of the link as well as the beam safety equipment. Cost considerations for the source, prime-generator or load will not be included, only transmission costs.

We will explore the safety and economics of wired and wireless power, where both ends of the transmission link are on the surface of the Earth, by briefly reviewing previous activities. This paper will then discuss some current investigations cost estimates and compare them to past wireless and wired power cost estimates or projections. Then conclusions will be drawn.

## GROUND WPT BACKGROUND

One of the authors (Dickinson) recalls being asked in 1976 by Sam Fordyce his NASA Headquarters sponsor to look into delivering electric power via microwaves to Manhattan Island from New Jersey over a particular 16 km range, as underwater cables were being overloaded and were expensive to install. This was after his successful managing of a demonstration in 1975 [5] of delivering over 34 kW of DC at 1.6 km at Goldstone, CA under the Contract Program Management by the other author (Maynard) when he was at Raytheon. We both thank Bill Brown very much for developing the rectenna [6] that was key to that project, and being its Technical Director.

The calculation performed for Fordyce determined that it would require a transmitting array and a rectenna array, both larger in diameter than the height of an 18 story building, in order to achieve over 90% beam coupling efficiency at 2.45 GHz over the distance required. After that shocking result, we looked elsewhere for potential applications, but found no critical or desirable sites. The end of the oil crisis and the National Research Council report [7] soon took the wind out of Space Solar Power (SPS) sails, and interest in WPT waned.

Thus WPT activities were mostly quiet until 1987 when the Canadians powered a model aircraft with rectennas near 2.45 GHz [8].

A contact from Exxon in Houston wanted to know if the energy from Alaska north slope oil could be converted to microwaves and delivered to Houston. An Alaska entrepreneur wanted to know if WPT could be used to supply electric power to native American stranded villages in his state. DOE began looking into delivering Alaska crude energy to Japan via beamed power. NASA's Center for Space Power at Texas A&M [4] along with DOE also began an investigation of conducting a demonstration of beaming power across a lake to a village in Alaska.

S. Bharj and colleagues at Sarnoff, powered the "Moonstruck" rover at 5.8 GHz with 450 W output at 200ft range (61m) in 1992 [9].

The Japanese conducted a demonstration of ground-to-ground power transmission at Yamasaki with the Kansai Electric Company [10] in 1994-95. They investigated beaming power from their mainland to islands in the Inland Sea. However, subsequently they encountered severe environmental concerns from the island residents and abandoned the investigation.

Ralph Nansen [11] endeavored to put together and conduct an approximately $50 M, 3-year demonstration in Texas of ground based photovoltaic power converted to 50-250kW microwave RF and beamed 1-5 km to a rectenna to be tied into the local utility's grid. The project did not materialize due to lack of funding.

provide the short term storage to bridge to medium term flywheels and to longer term natural gas turbines or pumped hydro storage for example.

The second potential WPT venue which surfaced in 1997-8 was in Eastern Canada across the Strait of Bell Isle that separates Newfoundland island from Labrador mainland. Here the distance is about 40 km and the desired power level was postulated to be about 800MW. In addition to cruise ships, there are occasional 60 m (several hundred ft.) tall icebergs that scour the strait bottom, giving underwater cable systems problems.

Again, due to weather and QOS considerations, 2.45 GHz is the ISM-Band frequency of choice. Thus the diameter of transmitters and rectennas for 90 % beam coupling efficiency must be over 97 m in diameter (29 stories tall) each if equal in size. In this case, the bulge of the Earth adds an additional 31.25 m height at each end for the beam to just be tangent to the Earth at the mid-point. Realistically, the ends of the terminal need to be sited at different elevations to minimize multipath propagation and for safety reasons there is a preference for the rectenna to be higher.

Terminals of the RF link should be based on mountain tops or hillsides in order for the beam to clear cruise ships. An investigation by Maynard revealed that such sites in the topography of the Bell Isle strait would require RF transmission distances from 65 to 88 km, not 40 km, thus increasing the required transmitter and rectenna diameters to over 130 m.

Similar beam safety and energy storage considerations apply as in the Singapore case, but due to the large quantity of power (0.8 GW), the prudent engineering design would be to have parallel pairs to provide redundancy for accommodating iceberg blockage and to permit down time for maintenance. Perhaps four 200MW links spaced more than an iceberg length apart should be used.

WIRED POWER SYSTEM COSTS

The least costly wired power transmission system is a 6 ft appliance cord at 10 A, 110V and $5 cost, and so its installed cost figure of merit (FOM) as shown in the comparison graph is over 10**3 $/MW-km.

The United States Department of Agriculture Rural Electrification Administration (REA) Bulletin [15] shows the results of a typical economic conductor analysis for a high voltage transmission line in support of a 200MW load at $160,000/mile, or for example at 100 km long, the FOM is over 10**2 $/MW-km, an order of magnitude cheaper than the appliance cord. There are economies of scale at work.

Obtained from the Asea Brown Boveri (ABB) web site is the cost of a 65 km undersea 200MW line between Finland and Estonia at a FOM of nearly 10**4 $/MW-km. Data for a 1.2 GW underwater link for the New York Power Authority to Long Island at 13 km range has a FOM that is about 80% of the ABB link, probably due to the larger power level that is carried. However, both are an order of magnitude over the REA line.

The approximately 1 GW, +/- 500kV DC line from the Dalles in Oregon to Sylmar in California around 2000 km has a FOM of installed cost of around 10**3 $/MW-km.

Based upon Bechtel studies in 1968 [16], a TE01 mode circular waveguide at 2 GW and 500 km length has a FOM of over 10**2 $/MW-km. An 8 GW nearly 1000 km system would have a FOM about half that, the lowest cost ( in then-year $) ground-to-ground wired system encountered.

Michael Klemke has estimated the cost of moving large quantities of electric power over intercontinental distances with

To the best of the authors knowledge, only a French proposal [3] is currently underway. On La Reunion Island in the Indian Ocean, the French are developing a beamed power system that is to be environmentally friendly to transmit power down a canyon to a resort complex at a lower elevation. The intent is not to fully compete on price of power delivery however. Funding continues to be a problem nevertheless.

## CURRENT WIRELESS POWER TRANSMISSION INVESTIGATIONS

Each author is involved indirectly with informal investigations into surface beamed power applications, *pro bono*. The first potential venue was from Singapore's large island to its other off-shore islands. The ranges involved are a maximum of 10 km and the power magnitude was 100 MW.

At 2.45 GHz, the S-Band Industrial, Scientific and Medical Band (ISM), the wavelength is ~12 cm and the equal diameter apertures at transmitter and rectenna for 90 % beam coupling efficiency are 48.6 m, nearly 160 ft, about 14.5 stories based on 11 ft per story.

Depending upon the overwater crossing utilization, it is estimated that an additional 42m of height may be required for the bottom edge of the power beam to clear the highest habitable spaces aboard cruise ships, and allowing for the curvature of the Earth. The message is that large structures are potentially involved in an area where high winds may occur. Hilltop locations would help the altitude requirements, if they are available, otherwise tall structures must be added to the system cost.

With further regard to weather, depending on the quality of service (QOS) desired for the electric power delivery, the sometimes torrential rains in Singapore need to be considered. The rain rates of up to 25 mm/hr are exceeded 0.3% of a year, ( 26 hours cumulative), and the attenuation can exceed 0.1 dB /km for 5.8 GHz ( 20.5% power loss in 10 km), and 0.007 dB/km for 2.45 GHz (1.6 % loss for 10 km) [12]. At rain rates of 100mm/hr, exceeded 0.03%/yr. (2.6 hr), the attenuation can exceed 0.8 dB/km at 5.8 GHz (84% loss), 0.025 dB/km for 2.45 GHz (5.6% loss) and 0.002dB/km for the 915 MHz UHF ISM-Band.

Although the 5.8 GHz ISM band frequency (wavelength of ~5 cm) could make the required apertures smaller by the square root of the frequency ratio, the weather losses are probably intolerable. The sizes at 915 MHz are correspondingly much larger, thus 2.45 GHz is the default choice.

In order to yield 100 MW of output ac power at 50 Hz for distribution, nearly 150 MW of RF needs to be generated at the transmitting array. The average power density over the aperture would be 82.4 kW/m2. However, the peak power density resulting from the requirement to support the nearly 10 dB edge taper that is required to place most of the power in the main beam and little in the sidelobes, will yield about 190 kW/m2 on axis. Further phase focusing on axis [13] at about 3.86 km range due to the requirement to have a spherical phase front converging on the rectenna, will yield 14 dB higher peaks, or 4.76 MW/m2 .

This is very hazardous to birds or other aviation and thus will require some means of detecting imminent beam crossings [14] coupled with interlocks to shut down the beam, until the crossing is complete. The beam interruptions will require the system design to accommodate the resulting voltage transients in the transmitter and receiver equipment safely.

There will also be required some form of on-line floating and switched energy storage in order to prevent the service interruptions to the customer. At additional cost, on-line batteries can

1. Mankins, J.,"The Space Solar Power Option," Aerospace America, pp. 30-36, May, 1997.

2. Brown, W.,"The History of Power Transmission by Radio Waves,"IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-32, No. 9, pp. 1230-1242, Sept. 1984.

3. Celeste, A., et al., "The Grand-Bassin Case Study: Technical Aspects," Proc. SPS'97, Montreal, pp. 255-258, Aug. 24-28, 1997

4. Haldane, R. and Schupp, B.,"Alaska '21: A Terrestrial, Point-To-Point Wireless Power Transmission System," Conference Proceedings, WPT'93, First Annual Wireless Power Transmission Conference, pp. 191-198, San Antonio, TX, Center for Space Power, Texas A&M, College Station, 23-25 Feb. 1993.

5. Dickinson, R.,"Microwave Transmission System for Space Power," Raumfahrtforschung, Band 20, Heft 5, pp 238-241, Oktober 1976.

6. Brown, W.,"The History of the Development of the Rectenna," Presented at the Rectenna Session of the SPS Microwave Systems Workshop, Johnson Space Center, Houston ,TX, Jan. 15-18, 1980.

7. National Research Council, *Electric Power From Orbit: A Critique of a Satellite Power System*, National Academy Press, Washington, DC, 1981.

8. Schlesak, J. and Alden, A.,"SHARP Rectenna and Low Altitude Flight Tests, Proc. IEEE Global Telecommunications Conference, New Orleans, Dec. 1985.

9. Bharj, S. et al.,"A Microwave Powered Rover for Space Exploration in the 21st Century," Conference Proceedings, WPT'93, First Annual Wireless Power Transmission Conference, pp. 449-455, San Antonio, TX, Center for Space Power, Texas A&M, College Station, 23-25 Feb. 1993.

10. Shinohara, N. and Matsumoto, H.,"Experimental Study of Large Rectenna Array for Microwave Energy Transmission," IEEE Trans. on Microwave Theory and Techniques, Vol. 46, No. 3, pp. 261-268, March 1998.

11. Nansen, R.,"Ground Test Program for Developing Solar Power Satellites," Space Energy and Transportation, Vol. 1, No. 3, pp. 187-194, 1996.

12. Flock, W.,"Propagation Effects on Satellite Systems at Frequencies Below 10 GHz, NASA Reference Publication 1108, Dec. 1983.

13. Hansen, R.,"Focal Region Characteristics of Focused Array Antennas," IEEE Transactions on Antennas and Propagation, Vol. AP-33, No. 12. pp. 1328-1337, Dec. 1985.

14.http://www.atlanticrt.com/jma7736.htm, JRC JMA-7736 Bird Watching Radar.

15. REA Bulletin 1724E-200, Design Manual for High Voltage Transmission Lines, Electric Staff Division, Rural Electrification Administration, U.S. Dept. of Agriculture, Washington, D.C. 20402, revised Sept., 1992.

16. Dunn, D. and Lowenstern, W.,"Economic Feasibility of Microwave Power Transmission in Circular Waveguide," Sect 3.6, Microwave Power Engineering, Vol. 1, pp., 256-269, Academic Press, NY, 1968.

17. Klimke, M.,"New Concepts of Terrestrial and Orbital Solar Power Plants for Future European Power Supply," Proc. SPS'97, Montreal, pp. 67-72, Aug. 24-28, 1997.

18. Dickinson, R. and Brown,W.," Radiated Microwave Power Transmission System Efficiency Measurements,"

normal-conducting HVDC cables, that translates into a FOM of under 10**3 $/MW-km [17].

## HISTORICAL WIRELESS POWER TRANSMISSION FIGURE-OF-MERIT COSTS

Proceeding mostly by distance, the first entry in the plot is the approximately 1.7 m range delivery of about 495 W done by Bill Brown and recorded by Dickinson in 1975 [18]. Based on the estimated development cost, the FOM is over 10**10 $/MW-km.

The next entry is the '94 Japanese Yamazaki test [9]delivering about 724 W at a range of 42 m, with an estimated FOM of slightly under 10**10 $/MW-km.

The slightly over $1M Goldstone test in '75 delivered 34 kW at 1.6 km for a FOM of about 1.8X10**7 $/MW-km.

Although not ground-to-ground, additional entries are given for the historical beamed power to model helicopter tests by Bill Brown (50 ft., 270W DC out) in the US in '65, and the model airplane tests in Canada and Japan in the SHARP '87 and MILAX '92 demonstrations, respectively. The authors did not have the detailed costs for the demonstrations, but based an estimate on prior knowledge and estimates of the number of staff involved, the time, the equipment quantity and complexity ,etc., in order to arrive at an approximate FOM. A similar estimate is given for the '95 demonstration in Japan of 3 kW delivered 50 m range to the 2.7m X 3.4m rectenna on the ETHER experiment on the HALROP airship [19].

The author's estimate of a full-blown airship system installed cost for 70,000 ft operation and over 1MW transmitted power is shown as near 10**6 $/MW-km FOM for today's $.

Among the lowest FOM WPT approaches are the Power Relay Satellites [20,21,22,23,24], at around 10**3 $/MW-km FOM. These systems are ground-to ground electric power delivery, but via orbiting reflectors, in order to get around the bulge of the Earth. The Bekey millimeter wave scheme (FOM $750-$1,375/MW-km) proposes a clever combination of pumped hydro storage to improve QOS and to provide a beam-safety zone around the over-water rectenna sites.

## CONCLUSIONS

The very short range (1-10m), preliminary demonstrations of WPT at low power levels (< kW) were in general quite costly, however, the cost estimates are coming down for larger power levels and longer ranges. Tens of km WPT systems are in the range of several $M/MW-km, whereas similar range wired systems are of order $10,000/WMW-km, at least two orders of magnitude less.

It is apparent from the plotted data points, and the indicated trend-lines, that longer range higher power level systems are estimated to be lower cost in $/MW-km. Both for the wireless and wired power transmission systems. However, their absolute costs are in $Billions, and only HVDC lines have been built to date.

Given the economic disparity and beam safety concerns, it is doubtful that short range WPT applications involving beams that are near tangent to the Earth's surface will ever be useful for electric power transmission as compared to wired power delivery. However, this does not preclude research and development tests and demonstrations of WPT from point to point on the Earth's surface, where economic competition is not the prime consideration.

## REFERENCES

NASA JPL Technical Memorandum 33-727, Pasadena, CA , May 15, 1975.

19. Fujino, Y., et al.,"Wireless Power Receiving System for Microwave Propelled Airship Experiment. *Space Technol*, Vol. 17, No. 2, pp. 89-93, Pergamon, Elsevier Science Ltd. 1997.

20. Ehricke, K.,"Space Technology and Energy," Presentation to the Space Science and Applications and the Energy Subcommittees of the Committee on Science and Astronautics, U.S. House of Representatives, SD 73-SH-139, 24 May 1973,

21. Rogers, T.,"Reflector Satellites for Solar Power," IEEE Spectrum, pp. 38-43, July, 1981.

22. Arrott, A.,"Power Relay Satellites," Workshop on Wireless Power Transmission (WPT) Strategic Partnering, pp. 41-46, A. D. Little at Dept. of Commerce, Jan. 31, 1994.

23. Woodcock, G.,"Power Relay Satellites," op cit. pp. 75-81, Boeing at DOC.

24. Bekey, I. and Boudreault, R.,"An Economically Viable Space Power Relay System," IAA-98-IAA.1.3.03, 49th International Astronautical Congress, Melbourne, Australia, Sept. 28- Oct. 2, 1998.

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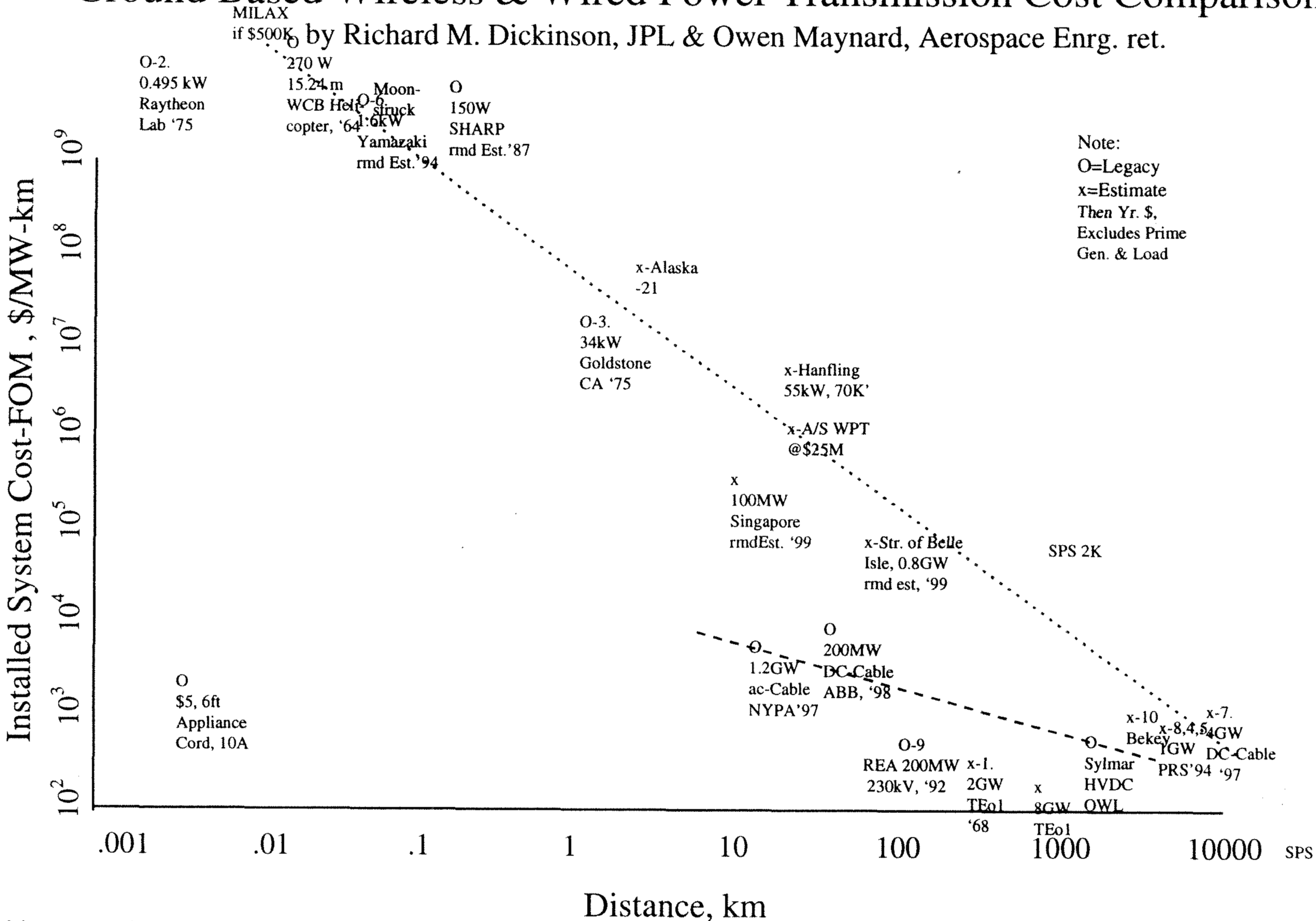


1. Dunn, D. & Loewenstern, W.,"Economic Feasibility of Microwave Power Transmission in Circular Waveguide," Sect. 3.6 Microwave Power Engineering, Vol. 1, pp. 256-269, Academic Press, NY, 1968.
2. Dickinson,R. & Brown,W.,"Radiated Microwave Power Transmission System Efficiency Measurements," Tech. Memo 33-727, Jet Propulsion Lab, Cal. Inst. Tech., Mar. 15,1975.
3. Dickinson, R.,"Evaluation of a Microwave High-Power, Reception-Conversion Array for Wireless Power Transmission," Tech. Memo 33-741, JPL-CIT, Sept1, 1975.
4. Ericke, K., "The Power Relay Satellites: A Means of Global Energy Transmission Through Space," Internal Document: Rockwell International, El Segundo, CA, 1973.
5. Rogers, T.,"Reflector Satellites for Solar Power," IEEE Spectrum, Vol. 18, No. 7, pp. 38-43, 1981.
6. Shinohara, N. & Matsumoto, H.,"Experimental Study of Large Rectenna Array for Microwave Energy Transmission," IEEE Trans. MTT, Vol. 46, No. 3, pp. 261-268, Mar. 1998.
7. Klimke, M."New Concepts of Terrestrial and Orbital Solar Power Plants for Future European Power Supply," Proc. SPS'97, Montreal, pp. 67-72, Aug. 24-28,1997.
8. Arrott, A.,"Power Relay Satellites," Workshop on Wireless Power Transmission (WPT) Strategic Partnering, pp. 41-46, A. D. Little at DOC, Jan, 31, 1994.
9. Rural Electrification Administration Bulletin 1724E-200, Design Manual for High Voltage Transmission Lines, U.S. Dept. of Agriculture, p. 9-7, Fig. 9-5, Sept. 1992.
10. Bekey, I. and Boudreault, R.,"An Economically Viable Space Power Relay System," IAA-98-IAA.1.3.03, 49th International Astronautical Congress, Sept. 28-Oct. 2, Melbourne, Australia, 1998.

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