Retail Beamed Power for a Micro Renewable Energy Architecture: Survey

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Abstract— **Retail delivery of electric power through millimeter waves is relevant in developing areas where the market for micro devices outpaces the power grid infrastructure. It is also a critical component of an evolutionary path towards terrestrial and space-based renewable power generation. Narrow-band power can be delivered as focused beams to receivers near end-users, from central power plants, rural distribution points, UAVs, stratospheric airship platforms or space satellites. The paper surveys the available knowledge base on millimeter wave beamed power delivery. It then considers design requirements for a retail beamed power architecture, in the context of rural India where power delivery is lagging behind the rapid rise in demand for micro-drives and connectivity.**

Keywords- micro renewable energy systems; space power grid; millimeter wave; power beaming, rural India power

I. INTRODUCTION

Despite low end-to-end efficiency, millimeter wave technology offers attractive architectures for rural beamed power delivery. In this paper we present reasons why retail beamed power transmission systems (BPTS) at such frequencies offer attractive options, viable in the not too distant future. There are no market-ready devices presented here, just an architecture in which such technology will fit. The paper is intended to trigger thought among the assembled experts at this symposium, and their colleagues in the community, on the possibilities.

Rapid development of an information-based economy creates a widely dispersed demand for small amounts of power, in developing parts of the world. Rural India is a prime example. Rapid acceptance of cell (mobile) phones shows popular apetitte for useful technology, even at costs that seem very high given the local income levels of the recent past. The same reasoning that helped popularize cellphones, viz, the utter inadequacy of the land-line telephone infrastructure, holds for the electric power grid as well. This poses a window of opportunity for options that are compatible with micro renewable energy systems at the single family level, and a space-based global solar power exchange. Retail beaming infrastructure bridges these.

Tesla [1] demonstrated that lamps could be lit at a distance using beamed electric power in 1893. Recently inductive charging of devices using resonant coupling has been shown [2]. As Vaitheeswaran [3] points out, the wired grid was preferred in industrialized nations where metal and concrete are abundant, power generation is centralized and the customer base is dominantly urban. In the USA, transmission and distribution losses dropped below 6% in 2001, rising [4] to nearly 8% by 2005 due to congestion. In poorer nations, theft of power and of the metal in the grid causes large losses beyond those due to aging equipment.

Until recently, the electric grid and communications infrastructure went hand in hand. India's extensive railway system was a leader in adopting wireless microwave communications. Recently, cellular telephony (the mobile phone) has become the preferred solution, reaching over 450 million accounts implying a large part of the 1.1 billion population. Comparing this to the 51% who lack access to the electric grid shows the opportunity for BPTS. A recent news item [5] is typical of innovation driven by the worldwide search for energy solutions. Two young men in southwest Africa are reported to have built a rudimentary wind turbine and generator out of scrap metal parts. They claimed to be seeking a non-human-powered alternative to their bicycle dynamo to power a home-built radio so that they could dance to music. The main customers of his wind turbine business came from his and neighboring villages to charge their cell phones. This illustrates the worldwide demand for microdevices leaping ahead of wired grid reach. The issue in our research is how best to use this demand to advance opportunities for much larger solution architectures.

I. LINK TO SPACE SOLAR POWER

Below we provide the rationale for exploring solutions in the millimeter wave regime from the perspective of aerospace concept development. Space Solar Power (SSP) [6,7], as considered by NASA [8-13], the National Research Council, [14], the Japanese Space Agency (JAXA) and the European Space Agency (ESA) [15,16] have focused their system architecture on microwave transmission below 10GHz. This is driven by the location of the photovoltaic arrays in Geostationary Earth Orbit (GEO) some 36,000 km above the equator, or on the Moon, some 300,000 km away. The large distance implies a receiver diameter of several kilometers and tropical location, offering little choice of transmission path during frequent cloudy weather. This forces a choice of frequencies that are relatively unaffected by water vapor, and the low frequency in turn forces the large system dimensions. In turn, each receiver must transact a large amount of power, requiring large grid modifications. The cost to first power, once estimated at $300 B at a time when the Space Shuttle was expected to deliver payloads to earth orbit for $220 per kg, is so immense as to be not worth calculating today. Japanese researchers showed high (38%) conversion efficiency from the solar spectrum to infrared laser beams using a Chromium-doped Nd-fiber laser [17], and have proposed a scalable architecture for solar power satellites using laser modules [18]. Recent US papers also appear to be considering laser transmission [19,20]; however, laser transmission through the atmosphere is mostly considered only for delivery to ocean-based receivers. Other JAXA concepts for trial SSP systems call for wide-area beaming from low earth orbit (LEO) photovoltaic satellites. This may be suitable over remote areas, for explorers and rescue teams to set up communications and charge other small devices. ESA emphasis appears to have shifted [21-23] towards developing terrestrial DC grids to connect renewable power generators in the North Sea, North Atlantic and photovoltaic arrays in the Sahara Desert.

II. SPACE POWER GRID

The Space Power Grid architecture [24-28] is an evolutionary, revenue-generating path to overcome the hurdle of Cost to First Power. In this architecture, initial public funding promotes the establishment of renewable power plants in remote areas, beaming and receiving power through a constellation of satellites. This enables these plants to reach customers located all over the world, and in particular, to fill the gaps in their own generation and smoothing the fluctuations that plague most renewable power technologies. This enables such plants to command the prices earned by baseload providers without requiring auxiliary generators. It has been shown that with a starting constellation of no more than 20 satellites in 2000km-high near-equatorial and sun-synchronous orbits, and about 100 participating power plants, an economically viable power exchange system can be set up, able to reach customers in most parts of the world with power from distant generating stations at reasonable cost of power. Once such a "grid" and market are in place, ultralight reflectors placed in high orbits would beam sunlight to collector-concentrator-converters placed on the low-orbit satellites that replace the first SPG constellation. Thus the addition of Space-based generation comes after the infrastructure and market are functioning, and is done incrementally using mostly commercial funding.

Transmission frequencies below 100GHz are not viable [25] because of the very large antenna size, and the attendant weight penalty on the satellites. There are acceptable transmission windows near 140 and 220 GHz. In rain, neither window offers acceptable transmission. On the other hand, because the satellites are not limited to equatorial orbits, alternative reception and transmission paths can usually be found. Several areas favorable for locating solar and wind plants are located in high deserts where humidity is low and rain is rare, and US rain data for instance show that there are major areas where rain periods are less than a few hours per year, making them ideal for generation and reception. Similar locations are postulated to exist around the world to make a real-time power exchange viable. The SPG system was projected to break even [27] in 17 years at a power cost of between $0.3 and $0.4 per KWh. The cost could be brought down to $0.2 per KWh with public funding covering the initial development and investment risk. A second generation of spacecraft built with revenue from these operations would then incorporate high-intensity solar collector-converters, and these would enable power delivery at less than $0.2 per KWh. To make the optimistic projection of $0.08 per KWh cited in some space agency reports viable, cost estimation must be done using something other than the published NASA-USAF space system cost database.

III. RETAIL BEAM DELIVERY

This paper deals with the retail delivery end of the architecture, where power beaming would best exploit the technology and market reach developed for a Space Power Grid. Chowdhary et al [29] considered the policy issues related to beaming of power at a retail level. Figure 1 shows the distances over which power can be beamed before the transmission efficiency comes down to 20 percent. When the amount of power needed is small, but its availability in the short term makes a big difference, beamed power wins out over wired grid construction. Ref. 30 shows that over short distances, beamed transfer is actually more cost-effective than wired transmission, even before considering all the benefits of wireless transmission. This is based on the $1M or greater marginal cost per kilometer cost of laying long-distance high-tension wired infrastructure. Reception points in the local grid will accept beamed power from Space or from line-of-sight towers conveying power from plants.

A. *Usage of Mobile Telephone Infrastructure*

It is reasonable to assume synergy with the existing mobile telephony infrastructure, because of the separation in wavelengths used, and the pinpoint nature of power beaming. The presence of strong electromagnetic fields at the antennae might interfere with cellphone signals [30,31]. An alternative is to co-locate the beamed power receivers with railway infrastructure where the railway reaches the villages to be served. These issues remain to be explored.

B. *Collocation of photovoltaic and mm wave antennae*

A technical development of immense potential interest is the finding that solar photovoltaic panels can serve as effective antennae for other forms of electromagnetic energy, including the millimeter wave spectrum [32-34]. Initial interest in this area comes from the noise introduced into the output of the solar panel by electromagnetic signals, and by the power radiated away by the solar panel. However, it appears that panels can be deliberately designed to serve as photovoltaic collectors and beamed power antennae simultaneously. This option has a high payoff in smoothing the power output of a solar installation and turning it into a baseload supplier.

IV BPTS MODEL FOR RURAL INDIA

There is surprising similarity between the space-space market, and the rural Indian market, for retail power beaming. In both cases, the terrestrial grid is inaccessible. Independent power sources and storage have to be installed for survival, and for basic communications. In both cases, there is strong usage of leading edge communications technology including space-based communications. The individual customer's power requirements are modest. The major differences are in the requirement for moving-target beaming and the much larger distances in the Space case, and the need to reduce cost to extremely low levels in the rural Indian case.

A. Power delivery to points of local distribution

As seen before, beamed power delivery becomes cost-effective at the final stage of distribution, where the power grid is unlikely to reach in the near term, and is very expensive. To avoid long-term health uncertainties, we will assume that the device-level delivery which includes indoor reception, occurs through wired charging points rather than wide-area wireless. Thus all BPTS use considered here is as point-to-point beams. Three different modes of delivery to the village-level distribution point can be considered. The first is by direct beaming from a power plant, relayed through towers on high points. The second is beaming from a stratospheric platform (stratoform). The third is through a satellite in a 2000 kilometer sun-synchronous orbit. Figure 2 compares the antenna diameters required for these options. Atmospheric attenuation varies [35] with distance at sea-level. Attenuation through the atmosphere at 45 degrees azimuth [36] shows a window at 220GHz with only 10% loss for dry air. While rain and fog effects are severe, dense cloud cover is usually limited to moving storm fronts. Hence alternative beaming locations can be found within a few miles. Where this is not feasible, such as in the Indian monsoon, additional storage appears to be the only option. The losses can be represented by the excess power factor to be applied at the transmitter to obtain the desired power at the receiver. Sea-level beamed transfer must be done using the 94 GHz window, where the excess power factor is 1.11 per kilometer, which means that 1.11 watts must be beamed for every watt that is received with the transmitter only 1km away. This shows why low-altitude beaming is at best a stopgap solution, since a beaming distance of even a few kilometers would bring efficiency down to less than 20 percent, and take the power factor well over 5, driving the cost beyond sustainable levels. For stratoform beaming, the beam must go up to 30km and then back down from 30km, while the transit loss between stratoforms is negligible. Here the power factor is 1.51. For the Space Power Grid first phase, where terrestrial power is beamed up to Space and back down to the receiver, the factor is 1.57; however, when space-based power generation is incorporated, the factor comes down to 1.21 because only one atmospheric transit is needed. Local distribution to rooftops within the last kilometer is better done at 220GHz to keep receiver sizes down. Stratoform and space beaming are best at 220GHz, also enabling direct transmission to rooftop antennae.

B. Long-distance grid

Where the wired grid does not reach the village, but must be beamed over several kilometers, the short-term feasibility and cost of the tower-based system must be traded off against the higher beam efficiency with the stratoform. The stratoform requires two passages through the troposphere. The rest of the transit is through high altitude rarefied air, above the weather and most of the water vapor. Thus with sufficient relay efficiency, the stratoform becomes the winning choice for most areas lacking primary terrestrial grids. It is also the better choice in case of natural disasters. During the most intense storms where the disturbances may reach far into the stratosphere, the stratoform will have to be grounded, but probably only for a few hours. The terrestrial tower relay on the other hand, requires an investment in permanent structures in remote areas, using hilltops wherever possible. These towers are also susceptible to damage in major storms, and will be downed by earthquakes and landslides. Satellite-based BPTS achieves transmission efficiencies nearly as high as the stratoform does, but is substantially more expensive and involves longer lead-time for development. The ground receiver antenna diameter may be 150 meters with 220GHz beams. A preferred option, when both systems are operational, may be to use stratoforms as relays for space-based beaming so that pin-point retail beaming from the 150m antennae on the stratoforms directly to rooftop antennae.

C. Baseline economic model for rural BPTS

With 72% of India's 1.1 billion population living in rural areas according to the 2001 census, and some 638,000 villages, the average village has a population of roughly 1700 and a land area of 100 hectares or square kilometer. While 80 percent of villages are believed to have at least one electric line, 52.5 percent of villagers (415 million people) are estimated to have no access to electricity [37]. This works out to roughly 100 million households, or roughly 150 homes per village. Modi [38] in 2005 estimated the number at 579 million. The 1sq.km area is a generous assumption since irrigated farm areas are usually included in this figure, allowing for a dispersed housing model. Many Indian villages concentrate houses in a small area for easy access to community resources and social gatherings, with the fields or forest resources surrounding this area. However, some of the most wealthy homes are likely to be located away from the center, and these are likely to be leaders in technology adoption. Thus the local distribution range is well within the "last kilometer" definition. As early as 1997 [39] cable television had penetrated a large number of villages, distributed from satellite receivers, with local fossil-fuelled generators powering the sets. Today, cellphone usage is prevalent, but owners often have to go far to charge them.

Since the villagers who lack access to electricity cannot be assumed to be able to pay the high cost of beamed power, the cost of power must be borne mostly by any community center and industry located in each village. At the first stage, with ground-level beam delivery over more than a kilometer, the power delivery factor is as high as 5, meaning that this is suitable only for low power levels such as those for communication devices and perhaps a few LED lights and emergency equipment. In the next stage we assume that each family uses 2.4KWh per 24 hrs, with the community and industry (C&I) picking up the rest of the 2920 MWh/yr. With the families paying only $01/Kwh, the C&I pay $21.5 per KWh. With SPG-based power delivery to a more developed community, the usage level goes up by an order of magnitude, and the cost is levelized at $0.2/KWh. This level will permit growth of local renewable sources, with many families generating enough to reduce their net power cost below the current $0.1/KWh, as energy independence grows. Assuming that each stratoform can deliver power simultaneously to 1000 receivers, and that each village is served by two stratforms, a fleet of nearly 1400 stratoforms are needed to reach all villages, which should take some 14 years totally to produce and deploy. The business case for this investment must be based on the economic development arising from power access, education, and sales of communication equipment.

IV. Technology Issues

McWilliams [40] surveys the state of the art of millimeter wave radar and terahertz imaging, at a time when gyratrons were the best sources. Bosq et al [41] have surveyed mm wave effects on other substances such as soils. Today solid state technology with phase-locked loops to obtain desired narrowband transmission appears to be the preferred option for generation. Johansson and Seeds [42] discuss generation and transmission of optical signals modulated by millimeter waves, using an optical injection phase-lock loop (OIPLL). Torkildon et al [43] discuss opportunities for outdoor millimeter wave networks. They point out that for given areas (antenna sizes), high frequency systems are substantially better (21dB advantage for a 60GB system over a 5GB system). They point to the possibilities for “electronically steerable arrays of compact printed circuit antennas” to realize highly directional links without manual pointing. Laskar et al [44,45] report that the frequency range of CMOS process technologies has increased to the point where low cost, highly integrated 60 GHz mm wave radio is possible, and 60GHz transceivers have been demonstrated as being suitable for high volume products. Voingescu [46] and Winkler [47] describes the solid state technology above 60GHz, and over 200GHz, as awaiting mass-production markets. Tracking antenna technology appears to have advanced enough to enable a large number of self-aligning phase array receivers to simultaneously track and communicate with beaming transmitters [48].

Indian Railways has accumulated extensive experience with microwave line-of-sight transmission along the railroad right of way [49,50]. SolarMitra Commonwealth advertises a solar photovoltaic powered microwave repeater system, where railway signals are transmitted between wireless towers [51]. The solar power sources with storage augment the wired power grid which is prone to frequent failures. One observation is that even with 7 GHz microwave communications, fog in river valley areas in a tropical climate causes signal outages [52].

Farinholt et al [53] have explored the use of energy transmitted through microwave to power distributed sensor nodes. They used a "microstrip patch antenna" which operated over the 2.4 GHz band to power a wireless sensing device used for structural health monitoring. The concept has been tested on real devices on the field and in the laboratory. They report excellent results even when the level of transmitted power was limited to low values (1W), which was sufficient to provide power for the sensor nodes. Their results break new ground towards new embedded devices that communicate and receive power over the same wireless network.

V. Relevance to a Micro Renewable Power Economy

In this paper we have tried to convey that millimeter wave technology has advanced to the level where tuning to specific lines in the 94 to 220GHz range is feasible with acceptable efficiency, and mass-produced chip arrays can be made at reasonable cost for use as transmitters and receivers. These can also be integrated with photovoltaic and other renewable power generators, and the beaming infrastructure can be synergized with cellphone and railway communications infrastructure. It is evident in the above that the cost of imported power will stay well above the $1/KWh level idealized in western power architecture. The utility is such power in the long term is to level the fluctuations in locally generated power. Integrating power receivers with local solar collectors is the first step towards this architecture. Extending this approach to wind, biodiesel and biogas generation helps to make all these technologies competitive and viable. The local beamed power infrastructure enables micro generators to be integrated into the local grid. In the long term, generation spikes prevalent with wind power will be used for electrolysis to generate hydrogen as the storage medium, and lead to a self-sufficient energy economy independent of fossil sources.

VI. CONCLUSIONS

1. Despite low end-to-end efficiency, millimeter wave power beaming is a viable alternative to bring electrification to rural areas, even in economically undeveloped areas. It can leap-frog the wired grid.
2. Direct beaming via towers, relay through stratospheric platforms, and a Space Power Grid constellation are considered. The stratoform is the best solution.

3. For low-altitude beaming, the 94 GHz band may be best suited, while for the stratospheric platform and Space Power Grid, the 220GHz window is most suited.
4. Digital Signal Processing and Phase-Locked Loop technologies enable selection of desired narrow bands for atmospheric transmission and conversion to and from the millimeter wave regime.
5. Synergy with cellphone and railway infrastructure offer immediate paths to establishing retail power beaming.
6. A growing body of research is advancing the synergy between photovoltaic receivers and phase array antennae for round-the-clock power conversion using direct sunlight and beamed millimeter waves.
7. Retail beaming technology offers a path to integrate direct conversion of solar power.
8. Indian village electrification offers an opportunity to establish a retail beaming infrastructure with a growing fleet of stratospheric platforms.
9. Contrary to popular misconception, low efficiency and weather issues are not show-stoppers for retail millimeter wave power beaming.

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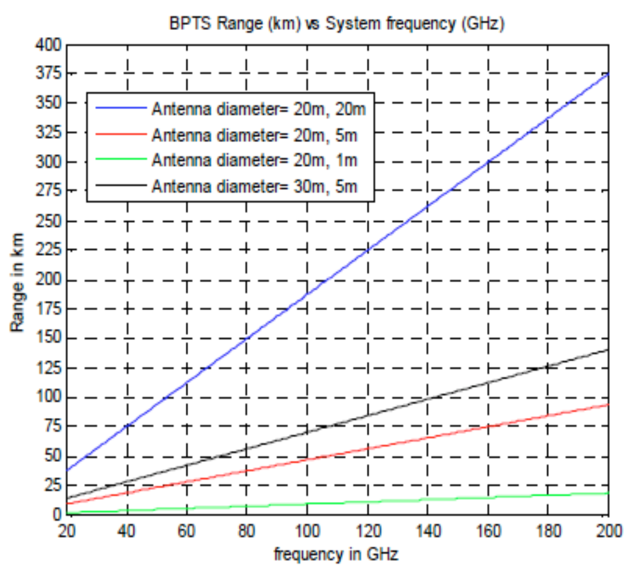

Figure 1: Range for 20% transmission efficiency, as a function of transmission frequency, for different combinations of transmitting and receiving antenna diameters. From Ref. [30], reproduced by permission of authors.

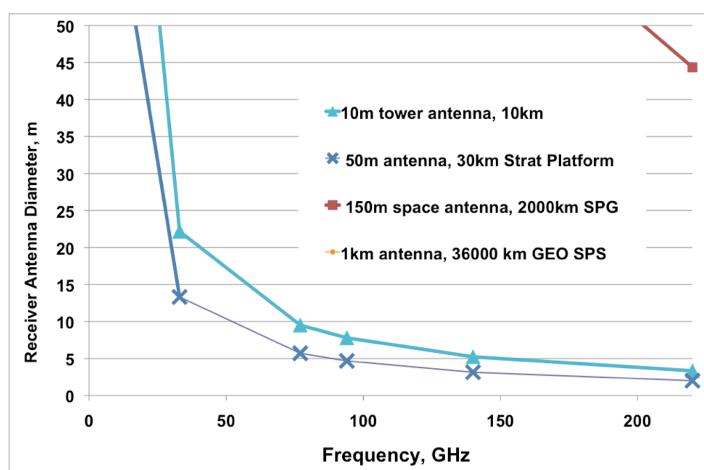

Figure 2: Comparison of receiver antenna sizes for various transmission options. Transmission from GEO results in very large antenna size at any frequency, as indicated by the data at the upper right corner. The stratospheric platform yields the smallest receiver size because of the moderate distance and the large transmitter or relay size possible.