Retail Beamed Power for a Micro Renewable Energy Architecture: Survey

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Retail delivery of electric power through millimeter waves is relevant in developing areas where the market for communication 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, tethered aerostats, stratospheric airship platforms, or space satellites. The article 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 demand growth for connectivity. A survey of technology developments relevant to millimeter wave beaming is conducted, and indicates that massive, mass-produced solid-state arrays capable of achieving good efficiency and cost effectiveness are possible in the near term to enable such retail power beaming architectures.

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1. INTRODUCTION
Despite present fears of low end-to-end efficiency, millimeter wave technology offers attractive architectures for rural beamed power delivery. In this article we present reasons why retail Beamed Power Transmission Systems (BPTS) at such frequencies may be 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 article is intended to trigger thought among the electronics and telecommunications community on the possibilities of synergy between the infrastructure for connectivity devices using embedded systems, and the infrastructure needed to enable very large numbers of their potential customers to access power for those devices. Micro renewable energy devices, as we define them here, denote devices that generate power from renewable resources,

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sized with a capacity ranging from a few watts, up to 3 kW. These are suitable for a single family or small shop.

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. Ready acceptance of cell (mobile) phones shows popular appetite 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, which is the 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 with a space-based global power exchange. Retail beaming infrastructure bridges these architectures of vastly differing scales.

Tesla [1893] demonstrated that lamps could be lit at a distance using beamed electric power. Recently inductive charging of devices using resonant coupling has been shown [Hadley 2007]. These are discussed later in this article. As Vaitheeswaran [2003] 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 [ABB 2007] to nearly 8% by 2005 due to congestion. In poorer nations, theft of power and of the metal in the grid, and delays in recovering from natural disasters, causes large losses beyond those due to aging equipment and low voltage.

Until recently, the electric grid and communications infrastructure went hand in hand. Radio reception pervaded India early, along with highly efficient and widely dispersed multilanguage print media catering to local needs. These created substantial awareness of the outside world, far in advance of physical transport infrastructure or the ability to communicate back into the outside world. India’s extensive railway system, which also accommodated the telegraph system along its right of way, was a leader in adopting wireless microwave communications. Recently, cellular telephony (the mobile phone) has become the preferred solution for retail connectivity, with over 885 million users reported at the end of June 2011 [TRAI 2011]. Although many urban customers have multiple accounts, this number still implies a significant 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 [Sheerin 2009] 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 nonhuman-powered alternative to their bicycle dynamo to power a home-built radio so that they could dance to music. The main customers of their wind turbine business came from neighboring villages to charge cell phones. This illustrates how the worldwide demand for small personal communication devices is leaping ahead of wired grid reach. In fact, the cost paid by impoverished customers for the first few watts or watt-hours of electricity is very high, as illustrated in Figure 1. The issue in our research is how best to use this demand to advance opportunities for much larger solution architectures.

2. SPACE SOLAR POWER INTERESTS

Shortly we provide the rationale for exploring solutions in the millimeter wave regime from the perspective of aerospace concept development. Space Solar Power (SSP) [Glaser 1968; Landis 2004], as considered by NASA [1995, 1984; Stancati 1996; Henley et al. 2002], the National Research Council [Council 2001], the Japanese Space Agency (JAXA), and the European Space Agency (ESA) [Geuder et al. 2004; anon 2004], has generally focused on microwave transmission below 10 GHz. This is driven by the presumed location of the photovoltaic arrays in Geostationary Earth Orbit (GEO) some
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36,000 km above the equator, or on the Moon [Criswell 2002], some 300,000 km away. The large distance to GEO implies a receiver diameter of several, even over one hundred, kilometers. This in turn implies massive grid infrastructure with a capacity of many Gigawatts built out from the receiver, to justify such size. Such stations will be few in number, and hence offer few alternative transmission paths during cloudy weather or rain. This forces a choice of frequencies that are relatively unaffected by water vapor, and the low frequency in turn locks down the large system dimensions. The cost to first power, once estimated at 300 billion US dollars 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 [Saiki et al. 2005], and have proposed a scalable architecture for solar power satellites using laser modules [Sasaki et al. 2005]. Recent US papers also appear to be considering laser transmission [Potter et al. 2008; Penn and Law 2002]; 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 [Trieb 2006; Summerer and Ongaro 2004; Geuder et al. 2004] towards developing terrestrial DC grids to connect renewable power generators in the North Sea and North Atlantic, and photovoltaic arrays in the Sahara Desert.

2.1. Space Power Grid Concept

The Space Power Grid architecture [Genk 2006] is an evolutionary, revenue-generating path to overcome the cost-to-first-power hurdle of SSP. The first argument in the Space Power Grid (SPG) concept is that efforts to win public funding of SSP, as a competitor to terrestrial renewable or nuclear power options, are doomed to failure. Instead, SPG argues for synergy with terrestrial renewable power generation, which also faces formidable obstacles that space technology can help overcome. 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 helps 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. Beyond finding high-valued markets for power from peak generation periods, real-time exchange will help such plants to command the prices earned by baseload providers by reducing the need for fossil-burning auxiliary generators. It has been shown that with a starting constellation of no more than 20 satellites in 2000 km-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 dynamic 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. Figure 2 from Genk [2006] illustrates the concept of the Space Power Grid. Transmission frequencies below 100 GHz are not viable [Komerath and Boechler 2006] because of the very large antenna size, and the attendant weight penalty on the satellites. This is illustrated by Figure 3. There are acceptable transmission windows near 140 and 220 GHz. In rain, neither window offers acceptable transmission. On the other hand, with a constellation of satellites in various 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. US rain data [Petty and Mahoney 2007], for instance, shows that there are major areas where rain periods are less than a few hours per year, making them ideal for generation and reception [Komerath et al. 2009]. 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 [Komerath and Komerath 2011a] in 17 years at a power cost of $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.

Recently, the feasibility of using millimeter waves for power delivery from space has been studied for an experiment to be conducted by the Boeing Company [Potter et al. 2011] using the International Space Station. Two generators are considered for installation on the ISS, which moves in an orbit roughly 400 km above Earth. One generates 10 kW of beamed power at 5.8 GHz, and the other generates 10 kW at 94 GHz using a solid-state conversion system. Since the transmitting antennae in the experiment are fairly small, it is expected that large receivers would be needed on Earth for full beam capture. Accordingly, the Goldstone Observatory antenna in Arizona, and a site in Florida, are chosen. During passages of the ISS over these locations, power received from the ISS is to be measured. The 5.8 GHz, 10 kW beam is expected to yield less than 100 watts at either location. The 94 GHz beam is expected to yield 7000 W at Goldstone, and roughly 4000 W at the Florida site where it is much more humid. Although numbers on generation efficiency are not available at present, it is a reasonable presumption that generation efficiency is expected to be quite high. Otherwise, a large radiator would be required to dispose of the several thousand watts of waste heat. The mass per unit power of the generator is also evidently quite high. Devices to generate several kilowatts at 94 GHz have been refined over the years, partly
due to military interest in this frequency for crowd-control beam weapons [Schamiloglu 2004].

Formidable issues remain, in implementing millimeter wave, dynamic power exchange between terrestrial sites and spacecraft, and in meeting the specific power (i.e., power delivered per unit mass in orbit) requirements of space-based millimeter wave generation from solar energy. The preceding arguments serve to point out why research directed at these obstacles is a worthwhile approach, compared to either arguing for public funding for GEO-based 5.8 GHz SSP demonstrators or waiting for a massive drop in space launch costs, both of which run counter to presently evident trends. Before going on to survey the prospects for millimeter wave power beaming technology, we now consider the retail power beaming end of the market requirements, to better understand the technology needs.

2.2. Relevance to a Micro Renewable Energy Economy

Power beaming at retail level removes the constraint of hard-wired grid connectivity, and enables connection of devices that are located in remote and mobile sites. The
connection can be both ways. Thus, for instance, one may consider beamed power to receivers located on automobile roofs, serving to charge electric vehicles as they drive on the highway or in parking lots. Less exotic applications might include colocating millimeter wave antennae on solar PhotoVoltaic (PV) panels and receiving beamed power at night while the PV arrays are otherwise not in use. During the day, excess power may be beamed back. Power may also be exchanged between millimeter wave generators and storage facilities located centrally in a village, and wind turbines or other generators. Such connectivity would greatly improve the utility of small renewable power generators, that suffer greatly from the unsteady nature of their sources. Hence, the availability of a retail power beaming architecture would make a huge difference to the utility of micro renewable power generators, and bring such distributed generation into the overall energy economy in a significant way. While such generators may be inefficient in generating electric power, the economic multiplier of such a capability is likely to be large, generating a growing appetite both for micro renewable devices, and for the retail beamed power market. It also stands to reason that millimeter waves will be the likely choice for such beaming, because the receivers must necessarily be small, and in line of sight with the transmitters or relays. Figure 4 illustrates some of these applications.

Chowdhary et al. [2009] considered the policy issues related to beaming of power at retail level. Where the amount of power needed is small, but its availability in the short term makes a big difference, beamed power wins over wired grid construction. Chowdhary et al. also show that over short distances, beamed transfer is more cost effective to install 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. It is evident in the preceding that the cost of imported power will stay well above the $0.1/kWh level idealized in western utility power architecture. In the short term such power enables connectivity and opportunity in parts of the world where the wired grid does not and is not likely to reach. In the long term beamed power allows renewable generators to level the fluctuations in locally generated power. The local beamed power infrastructure enables micro generators to be integrated into the local grid. Trade studies will determine whether micro renewable generators should beam their power spikes back into the grid, or whether they should use those to generate stored energy media such as hydrogen.

2.3. Commonality between Space and Rural Power Beaming Issues

There is surprising similarity between the space to space power market and the rural Indian market, to justify retail power beaming. In both cases, the wired 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. Note that many spacecraft require less than a kilowatt. The major differences are in the requirement for extremely precise 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 case.
2.4. Atmospheric Propagation Considerations

The atmosphere attenuates electromagnetic beams. Four types of attenuation are usually considered.

(1) The first is free-space spreading from an isotropic antenna, which is proportional to the square of distance. This is minimized down to the diffraction limit using transmitters with very high gain, that is, by focusing as tightly as possible.

(2) The second is spillover loss, or failure to capture all of the radiation reaching the receiver location. The diffraction-limited beam typically has a main lobe containing roughly 84% of the power that reaches the receiver location. Textbook designs for low-frequency microwave receivers typically aim to capture only the main lobe, because of the size constraint. However, with millimeter waves (and with laser optics) it should be possible to design the receiver to capture the second lobe as well, permitting up to 98% capture. The size difference is roughly a factor of 1.55 in antenna diameter.

(3) Attenuation by air is ascribed to absorption by gaseous nitrogen, oxygen, and water vapor. Both temperature and pressure are important. The first effect is that of density, so that as altitude increases, attenuation decreases. The second is of the actual water vapor content in mass of water vapor per unit volume. Thus, for a given relative humidity, increasing altitude and decreasing temperature imply a decrease in water mass per unit volume. For a standard atmospheric temperature lapse rate, rising from sea level to 4,000 meters brings roughly a 27-degree Celsius drop in temperature, which implies up to a 6 dB drop in attenuation.

(4) The fourth is scattering by solid (dust or ice) or liquid (rain or cloud) particles. Above cloud level, water and ice droplet concentration is very low, so that the biggest problem with millimeter waves, that of rain, is also minimal.

Some of these effects can be seen in Figure 5, from work done by the US Federal laboratories and NATO [Petty and Mahoney 2007; Liebe et al. 1985; Liebe and Layton 1987; Liebe and Hufford 1989] which shows horizontal attenuation in dB/km over the microwave and millimeter wave regimes. The upper curve is for a case of 75%
Fig. 6. Need for burn-through is illustrated by the severe attenuation of millimeter waves through humid air. Data from Liebe et al. [1985].

humidity at sea level, while the lower curve is for nearly dry air at 4 km altitude. These models show that there are several good frequency windows for propagation through the atmosphere, other than the low-frequency one below 10 GHz. The windows near 94 GHz, 140 GHz, and 220 GHz are of particular interest. There are already practical, portable, high-power converters in the 94 GHz regime, developed for military and police applications. The 140 GHz regime has been used in concept studies for beamed propulsion from Earth to space-launch vehicles, presumably corresponding to some high-power sources that may become available for such applications. The 220 GHz window has found both military and civilian applications, primarily for imaging and radar. We find this window to be attractive because of the strong need to minimize receiver size and mass for space beaming applications.

The issue of vertical transit through the atmosphere has been considered by astronomers. Data on propagation come from the Mauna Kea observatory in Hawaii, which is located 4205 meters above sea level, in a region which enjoys clean air. These data, easily found on the Internet, show that transmission is above 99% below 10 GHz, above 98% for the 94 and 140 GHz windows, and above 97% near 220 GHz. Given the large advantage in receiver size, these data present a clear case to select the 220 GHz window, provided the low-altitude humidity and weather issues can be avoided as indicated in the prior paragraphs. The effect of atmospheric transit at a 45-degree inclination to the zenith has been presented in Petty and Mahoney [2007], and drives a similar conclusion. It shows roughly 90% transmission near 220 GHz.

The effects of relative humidity are considered in Figure 6. The figure is constructed from the predictions in Liebe et al. [1985], for sea level air at the highest temperature considered, which is 310 K. This is taken to be most relevant for Indian surface conditions. Again, the net conclusion is that horizontal propagation of millimeter waves at
sea level is to be avoided as much as possible. These considerations impact the architecture described in this article. More exotic ideas, such as the burn-through effect of continuous beaming at high power levels, are considered later in the article.

3. FOUR-STAGE MODEL FOR A POWER BEAMING ARCHITECTURE

In the following, a 4-stage model is considered. Some idea of the range of applicability can be obtained simply from line of sight considerations as shown in Figure 7. The terrestrial power grid will primarily be supplied from power plants located in the region. This grid will reach district capitals and major towns, and be available along the railroad system. From points on this grid, power can be beamed efficiently over short distances using the infrastructure for mobile telephony, as well as by using antennae located on hills and ridges. The four stages are as follows: (Figure 3 compares the antenna diameters required for these options)

1. beaming across nations between major plants via satellites;
2. beaming from regional plants, to stratospheric platforms distributing to local reception points or aerostats;
3. beaming from local mini-power plants via tethered aerostats;
4. last-kilometer beaming using mobile phone / railway telecom infrastructure.

3.1. Beaming across Nations between Major Plants via Satellites

At levels of tens of megawatts, beaming through space or between high-altitude platforms, becomes a practical alternative for the future. An India-US power exchange using 4 to 6 satellites is discussed in Dessanti et al. [2011], using the SPG architecture. 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 multiplier to be applied at the transmitter to obtain the desired power at the receiver. For the SPG first phase, where terrestrial power is beamed up to space and back down to the receiver,
the multiplier 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.

3.2. Beaming from Regional Plants, to Stratospheric Platforms Distributing to Local Reception Points

The second alternative is beaming from a stratospheric platform (stratoform), which is a large, lighter than air inflated structure. Such platforms have been proposed for solar and wind power generation, and hence have been conceptualized with both the large area needed for an antenna to receive power from space, and the propulsive ability to stay stationary in high-altitude wind streams. Both stratoform and space beaming are best at 220 GHz, also enabling direct transmission to rooftop antennae where the weather allows.

Where access to the wired grid is several kilometers away from a village, the short-term feasibility and cost of a tower-based system must be traded off against the higher beam efficiency with the high-altitude platform, whether it is a stratospheric platform or an aerostat tethered to stay in the troposphere. Stratoform beaming requires two passages through the troposphere. The rest of the transit is through high-altitude rarified 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. A terrestrial tower-based 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, landslides, and high winds. Satellite-based beamed power transmission 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 220 GHz beams. A preferred option, when both systems are operational, may be to use stratoforms as relays for space-based beaming to enable pin-point retail beaming from the 150 m antennae on the stratoforms directly to rooftop antennae.

3.3. Beaming from Local Mini-Power Plants via Tethered Aerostats

For transmission over a distance larger than about 5 km, a practical and effective way is using tethered aerostats. Tethered aerostats have been described by many authors, for instance Krausman [2005] and Peterson [2005]. Our recent studies indicate that the aerostat architecture offers some interesting options to improve the effectiveness of rural power beaming.

Pant et al. [2011] discuss the use of tethered as well as powered Lighter Than Air (LTA) platforms such as aerostats in rural power beaming. Tethered aerostats are feasible, where the aerostat is anchored at altitudes as high as 4000 to 5000 meters. This fact opens up the possibility of relaying most horizontal propagation between aerostats at altitudes where the air is both dry and rare enough to eliminate most of the losses. Komerath et al. [2011] discuss the option of sending millimeter wave power through waveguides built into the tethers used with aerostats at 4000 m altitude, as a way to tunnel through the lossy transmission through the troposphere. The dimensions of the tether waveguide are compatible with the choice of 220 GHz as the beaming frequency. The added weight of the metal waveguide within the tether appears to be quite manageable, within the demonstrated envelope volumes of aerostats. The antenna structure and related paraphernalia can be placed inside the gas envelope of the aerostat, close to the center of gravity. This option, if successful, can break through
the primary objection to the use of millimeter waves, which is the vulnerability to moisture and the loss due to the dense air near the surface.

3.4. Last-Kilometer Beaming Using Mobile Phone/Railway Telecom Infrastructure

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. 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.

The last delivery step inside a village home is thus still likely to be using AC or DC power through wires wherever practical, to reduce expense and technology level. Sea-level beamed transfer may be done using the 94 GHz window, where the excess power multiplier is only 1.11 per kilometer, which means that only 1.11 Watts need be beamed for every watt that is received with the transmitter only 1 km away. This shows why low-altitude beaming is at best a stop-gap solution, since a beaming distance of even a few kilometers would bring efficiency down to less than 20% and take the excess power multiplier well over 5, driving the cost beyond sustainable levels. For stratoform beaming, the beam must go up to 30 km and back down, while the transit loss between stratoforms is negligible. Here the excess power multiplier is 1.51. Local distribution from high-altitude platforms to rooftops within the last-kilometer is better done at 220 GHz to keep receiver sizes down.

3.5. 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 pin-point nature of power beaming. The presence of strong electromagnetic fields at the antennae might interfere with cellphone signals [Drapalik et al. 2010; Costia et al. 2010]. An alternative is to collocate the beamed power receivers with railway infrastructure where the railway reaches the villages to be served. These issues remain to be explored. Concerns have been expressed regarding the effect of millimeter beams on metal towers. The best answer may be that the receivers must be placed a short distance away from the towers themselves, but close enough for maintenance access.

3.6. Baseline Economic Model for Beamed Power Transmission to Rural India

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 kilometers. While 80% of villages are believed to have at least one electric line, 52.5% of villagers (415 million people) are estimated to have no access to electricity [Shrestha et al. 2004]. This works out to roughly 100 million households, or roughly 150 homes per village. Modi [2005] in 2005 estimated the number at 579 million. The 1 square kilometer 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 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 definition of the last-kilometer that power has to reach. As early as 1997 [Press 1999] 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 excess power multiplier is high, meaning that this is suitable only for low power levels. Such levels are suited to communication devices, lighting systems based on Light-Emitting Diodes (LEDs), and emergency equipment. In the next stage we assume that each family uses 2.4 kWh per 24 hrs, with the community and industry (C & I) picking up the rest of the 2920 MWh/yr. With the families paying only $0.1/ kwh, the C&I pay $0.215/ 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 ideal of $0.1/ kWh, as energy independence grows.

For longer distances and larger amounts of power, stratospheric platforms [Krausman 2005; Peterson 2005] offer the best promise. Assuming that each stratoform can deliver power simultaneously to 1000 receivers, and that each village is served by two stratoforms, 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 advances in standard of living, and sales of communication equipment.

4. TECHNOLOGY ISSUES
The entire spectral range from 100 GHz to 1 THz poses intriguing opportunities. This regime spans the transition between traditional electronics and photonics, and hence, legacy methods from both the microwave and laser optics communities come into play, with interesting possibilities for integrating these. Applications of millimeter waves arise in many fields, and the opportunities are just beginning to be realized. Uses in detecting weapons and contraband using various properties of the human skin, tissue, thermal characteristics of materials, emission spectra, and scattering characteristics of textiles are summarized in Appleby [2007]. A modern approach [Crowe et al. 2005] is to develop solid-state circuits that use nonlinear diodes to extend microwave technology to much higher frequencies. At another end of the technology spectrum, light is used directly to generate millimeter waves.

The essential subsystems for beaming power are the power transmitter and the power receiver. The power transmitter embodies the power beaming station where ElectroMagnetic (EM) energy is harnessed to a suitable wavelength that can be beamed to the receiver without significant loss in the transmitting medium. The power receiver is the electric power generation station where the beamed EM energy is transformed into electricity. Economical utilization of this energy requires very high energy conversion efficiencies at the beaming and receiving stations.

4.1. Conversion of the Solar Spectrum to mm-Wave Energy
Solar energy abounds in space. Most of the energy is available in the visible range of the EM spectrum but there is a significant amount of energy in the ultraviolet region compared to the spectrum at sea level [Hulstrom et al. 1985]. Considering a particular photon in the green wavelength of 532 nm, the frequency of the corresponding EM wave is 564 THz with a quantum of energy 2.33 eV. Therefore, a green photon needs to be converted to 2560 photons of frequency 220 GHz each for 100% conversion efficiency. This is a daunting task.

Direct wavelength conversion techniques such as optical heterodyning or wavelength mixing for frequency down-conversion would require nonlinear optical elements and the conversion efficiency is expected to be extremely low. Booske [2008] reviewed the
challenges in frequency conversion and summarized data showing that the output power of solid-state devices is very low (100 mW). Thus very large arrays of such solid-state devices will be required for high-power applications. Vacuum devices can generate large amounts of power (1 MW) in the 200–250 GHz range. Although vacuum devices are proven good for producing high-power microwaves, their specific output power (output power per unit mass of the equipment) is low. On the other hand, solid-state devices do not offer nonlinear scaling advantages as power level is increased.

Filip et al. [1997] showed theoretically that microwaves (electromagnetic radiation in the GHz range) can be produced by controlled motion of electrons in a vacuum in the presence of electric and magnetic fields. Their vacuum microelectronics device consisted of a capacitor, a cathode, and an anode, and they showed that the electrons follow a cycloid-like trajectory. High acceleration of the electrons during this curvilinear motion leads to the generation of microwaves. Typical values of the speed and acceleration of electrons in their study were on the order of $10^6$ m/s and $10^{17}$ m/s$^2$, respectively.

Energy is radiated when a charged particle moves in a magnetic field, leading to cyclotron and synchrotron radiations at nonrelativistic and relativistic velocities of electrons, respectively. Egorov et al. [2006] and Roy et al. [2007] investigated high-power millimeter wave generation using nonrelativistic electrons in a retarding electric field, that is, using decelerating electrons. The work of Egorov et al. is particularly interesting because they formed an electron beam with an electro-optical system and studied the oscillations of the beam using a diode scheme. These devices, however, require an external electricity generator to produce electrons and to create the electric field for accelerating or decelerating the electrons.

Electrons can be produced by six methods.

1. Auger electron emission, which occurs due to radiationless transitions of electrons between orbital energy levels. Ionized atoms can lose energy by releasing an Auger electron instead of emitting a photon, and the Auger electron acquires its kinetic energy from the radiationless transition.
2. Field emission, which occurs when a strong electric field is applied to a metal.
3. Photoemission, which occurs when photons, that is, EM waves excite electrons to the vacuum energy level as in the photoelectric effect.
4. Radioactive nuclear decay, which produces negative beta particles.
5. Secondary electron emission, which occurs when atoms are excited by charged particles including electrons.
6. Thermionic emission, which occurs when a metal is heated.

Electromagnetic radiation itself can be produced by three basic methods: (i) charged particle acceleration or deceleration, (ii) electronic transitions in ionized or excited atoms, and (iii) nuclear reactions. Photoexcitation is an approach to produce electrons in the conduction band of a semiconductor by exciting electrons from the valence band. This can be achieved using incident sunlight. The conduction band electrons can be accelerated or decelerated using the built-in potential of p-n junctions depending on whether the electrons are injected into the junction from the n-side or p-side, respectively. The radiation emitted by electrons during deceleration is known as bremsstrahlung (i.e., braking) radiation. The wavelength of the radiation depends on the magnitude of the acceleration and deceleration, and the emitted radiation is highly directional at certain angles around the direction of the electron velocity as shown in Figure 8. Numerous factors affect the efficiency of converting the sunlight into electromagnetic waves in the GHz range, including the dopant concentration, built-in potential across the p-n junction, geometry of the p-n junction (flat versus pointed junction), photogenerated electron density, polarization of the incident radiation, types of substrate (narrow bandgap (e.g., Si of bandgap 1.1 eV) versus wide bandgap (e.g.,
Crystalline silicon carbide (SiC) has excellent thermophysical properties and mechanical strength. It is chemically inert and resistant to radiation damage. This radiation-resistant property makes it suitable for applications in space and other harsh environments. Some of the properties of SiC and Si are listed in Table I. High thermal conductivity and high junction temperature indicate that SiC p-n junctions can be used at high temperatures. Also high bandgap and high electrical breakdown strength indicate that SiC p-n junctions will have high built-in potential and the electrons can be accelerated more at the SiC p-n junction than at the Si p-n junction. Additionally the higher bandgap of SiC indicates that the photons in the visible and near-UV range can be used efficiently to generate photoexcited electrons in SiC semiconductors. The cost of crystalline SiC, however, is much higher than that of Si. Other materials may be used or other methods may be investigated to lower the cost of producing crystalline SiC.

Two p-n junction-based solid-state devices for conversion of sunlight to millimeter waves are conceptually illustrated in Figure 9. Since sunlight is randomly polarized, a linear polarizer is used to select only a unidirectionally oscillating electromagnetic field of the light. While some of the light creates photoexcited electrons, lights of other wavelengths can be used to inject electrons into the p-n junctions. The p-n junctions are connected in series to accelerate (or decelerate) the electrons successively in the p-n junctions as the electrons travel back and forth due to the oscillating electromagnetic field of the incident light. This mechanism is expected to yield more EM radiation from the same electron. Another design of the device uses azimuthally polarized light. In this case, the electrons move in a circular track and emit EM radiation as they accelerate or decelerate at the p-n junctions.

Another aspect of this p-n junction device is that the operating principle of an antenna can be applied to transform the solar energy into electromagnetic waves in the GHz range. Since the electrons and holes accumulate at the ends of the depletion layer across the p-n junction, the depletion layer can be considered to form a dipole of length equal to the depletion layer width. The oscillating electric field in the electromagnetic waves of the sunlight can be utilized to oscillate the dipole in order...
to emit electromagnetic waves with frequency in the GHz range. The resistance and capacitance of the depletion layer can be designed to achieve this type of down-conversion with possibly high conversion efficiency. Salama et al. [2003] fabricated an antenna-coupled Schottky diode for frequency mixing that operated at about 94 GHz. The conversion of solar quanta in space directly into a suitable quantum which can be transmitted to the Earth with minimal transmission loss provides one option for wireless power transmission. Karalis et al. [2008] used two coils of diameter 60 cm each to produce radiofrequency energy and supplied power to a 60 W light bulb wirelessly with 40% efficiency from a distance of 2 m in 2007. Intel Corporation [Schneider 2010] demonstrated 75% efficiency in supplying power to a 60 W light bulb wirelessly from a short distance. Mohammed et al. [2010] presented a historical perspective of wireless power transmission and reviewed microwave generators in various frequency ranges such as 2.45, 5.8, 8.5, 10 and 35 GHz.

4.2. Generation and Conversion of Millimeter Waves
McMillan [2006] surveys the state-of-the-art of millimeter wave radar and terahertz imaging, at a time when gyrotrons were the best sources. Kartikeyan et al. [2004] and Nusinovich [2004] give excellent discourses on the technology of high-power millimeter wave generation using gyrotrons. Schamiloglu [2004] has surveyed high-power microwave generators, specifically about applications to nonlethal directed energy weapons.

Today solid-state technology appears to be the preferred option for generation. Phase-locked loops are used to obtain narrow frequency bands. Johansson and Seeds [2003] discuss generation and transmission of optical signals modulated by millimeter waves, using an Optical Injection Phase-Lock Loop (OIPLL). Voingescu [2006] and Winkler et al. [2005] describes the solid-state technology above 60 GHz, and over 200 GHz, 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 [Miyamoto et al. 2003].

The possibility of generating millimeter waves by resonance of a microspherical cavity has been considered by Ilchenko et al. [2000]. Microspherical whispering-gallery modes of a toroidal lithium niobate cavity electro-optic modulator were superposed with a stripline resonator. Preliminary results showed resonance Quality (Q) factors exceeding 5 million in a 9 GHz prototype, and a 33 GHz prototype was being tested. With efficient coupling of light in and out of the resonators, and high-purity silica, Q factors of over 10 billion are projected. Wake et al. [1995] describe a way to generate millimeter wave signals using optical input. A dual-mode multisection distributed feedback semiconductor laser is used to generate high-power signals between 40 and 60 GHz with excellent spectral purity and stability.

Razavi [2008] describes an inductive feedback technique that substantially raises the maximum speed of resonant circuits, allowing them to operate near the self-resonance frequency of the inductors. Optical heterodyning techniques using laser beams directed at ultrafast photodiodes has been used by Wake et al. [1995] to obtain narrow linewidths and excellent phase uniformity.

Waveguides for millimeter waves are considered by Hirshfeld et al. [2005] who describe a high-power harmonic generator for infrared and millimeter wave regimes. Theoretical analysis and computations suggest the use of a uniform dielectric-lined waveguide in an efficient generator at 103 GHz, using a 34.2 GHz drive beam. A bunched beam injected into such a waveguide generates intense radiation at a harmonic of the injection frequency. The phase velocity of the design mode of the structure must be synchronous with the beam velocity. Samoska and Leong [2001] describe two Monolithic Microwave Integrated Circuit (MMIC) power amplifier designs using InP HEMT technology. One covers the WR10 and WR8 waveguide bands (75–110 GHz and 90–140 GHz). The other is optimized for the WR10 band, providing over 13 dB large signal gain over the 75–110 GHz and output power of 40–50 mW. Wang et al. [2001] describe a further set of W-band power amplifier modules using MMICs, for local oscillators of a far-infrared and submillimeter telescope. The highest frequency power amplifier covers 100–113 GHz and has a peak output power greater than 250mW at 105 GHz. Waveguide fabrication techniques are described in McGrath et al. [1993].

The most convincing demonstration seen to-date on the deployment of Megawatt-level millimeter wave beams and waveguides with good efficiency is the work of Verhoeven et al. [1998]. They reported generation of over 750 kW, continuously tunable over the range from 130 GHz to 260 GHz, using a MASER (microwave amplification by stimulated emission of radiation) powered by an electron beam. They cited over 50% overall efficiency. The apparatus was designed for long (100 millisecond) pulses in the given frequency range, with pulse power levels exceeding a Megawatt. They declared the feasibility of going up to 5 MW and continuous-wave emission in future. Their equipment used physical waveguides to contain and amplify the millimeter waves.

4.3. Nano-Antennae, Large-Array MMICs and Beam Steering

A digital beam-forming antenna for the 25–30 GHz range, for operation on stratospheric platforms has been described by Oodo et al. [2000]. Goswami [2004] review emerging developments in solar energy. Among these is direct conversion using nanoscale antennas with efficiencies exceeding 80 and possibly 90%. These exploit the wave nature of light, and envisage broadband rectifying antennae. These would have nanoscale dimensions to capture wavelengths in the submicron range. In this way, the fundamental band-gap limitations of photovoltaic semiconductor cells can be avoided, enabling high efficiency. By the same argument, nanoscale antenna elements could also be developed.
tuned to given millimeter wave. Wang et al. [2004] discuss the antenna effect in receiving and transmitting light like radio waves using random arrays of aligned carbon nanotubes. They show response consistent with the theory of conventional radio antennae. They postulate that carbon nanotubes interact with light in the same manner as simple dipole radio antennae. The reflected signal is suppressed when the electric field of the incoming radiation is polarized. There are interference colors in the reflected light from an array, because of the length matching antenna effect.

Torkildson et al. [2010] discuss opportunities for outdoor millimeter wave networks. They point out that for given areas (antenna sizes), high-frequency systems are substantially better, with a 21 dB advantage for a 60 GHz system over a 5 GHz 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. [2007] and Pham et al. [1998] report that the frequency range of CMOS process technologies has increased to the point where low-cost, highly integrated 60 GHz millimeter wave radio is possible, and 60 GHz transceivers have been demonstrated as being suitable for high-volume products. Nicholson et al. [2007] describe a low-voltage, small form factor chipset for 77 GHz automotive and imaging applications. The chipset is fabricated in 0.12 micron SiGe HBT technology. A fine lithography SiGe BiCMOS process is chosen as an attractive technology to meet digital signal processing requirements in the millimeter wave spectrum, into the 200 GHz range. A fully integrated 2.5V, 77 GHz transceiver with PLL is described. A solid-state 200 GHz experimental radar is described by Essen et al. [2007].

In the field of radar applications, there has been intense effort on millimeter wave generation, pointing, reception and interpretation, along with studies of atmospheric effects. Brookner [2002] summarizes the state-of-the-art and trends in MMIC phased arrays. He describes an electronically steerable plasma mirror, where a plasma sheet is rotated to steer the beam in azimuth, and electronically tilted to steer the beam in elevation. A 50 cm by 60 cm plasma mirror is described. While several high-end options being developed under the US Defense Advanced Research Projects Agency (DARPA) sponsorship are indicated, Brookner also points to low-cost mass-produced 77 GHz phased arrays for automobiles. Here separated antennas are used for transmission and reception, with their beamformer networks photo-etched on a sheet of copper-clad dielectric. Each antenna consists of series-fed columns of patch radiators. The beam-formers are Rotman lenses. Beams are scanned in azimuth by switching between input ports of the Rotman lens.

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 [Petty and Mahoney 2007; Gliese et al. 1998; Yao 2010]. 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 [Drapalik et al. 2010]. However, it appears that panels can be deliberately designed to serve as photovoltaic collectors and beamed power antennae simultaneously. This option has a high potential payoff in smoothing the power output of a solar installation and turning it into a baseload supplier.

4.4. Conversion of Millimeter Wave Energy to Electricity

At the power receiving station, the millimeter wave energy must be converted to electrical energy in either direct current or alternating current mode to suit end-user devices. One nonelectrical option may be to use the millimeter waves to heat liquids and generate steam to run electrical generators; however, this is an inefficient use of beamed energy in most terrestrial applications. It does offer an inexpensive option for energy storage at the receiver, and hence may be an option in emergency response situations.
applications. Another approach is the direct conversion of the mm-wave energy to electricity using a solid-state device, such as a rectenna which is a rectifying antenna. The construction of a simple rectenna would be a dipole antenna containing a Schottky diode across the dipole elements. The incident mm-waves induce an Alternating Current (AC) in the antenna and the diode rectifies the AC to direct current. The Defense Advanced Research Project Agency [Raghunathan et al. 2005] investigated a rectenna array for harvesting energy from infrared waves. Corkish et al. [2002, 2003] discussed rectennas for solar energy conversion and their conversion efficiency. De Vos [1992] and Berland et al. [2003] reported that the limit of the conversion efficiency is 85.4% for a nonenergy-selective collector. However, De Vos [1992] also pointed out that the conversion efficiency can be increased to 86.8% in thermal converters by absorbing multiple wavelengths in multiple materials having different bandgaps. Ries [1983] and Wright [2000] showed theoretically that the ultimate conversion efficiency, that is, the Landsberg limit [Green 2003; Richards and Shalav 2007] of 93.3%, can be achieved using a rectenna assembly consisting of nonreciprocal absorbers such as optical circulators.

5. DISCUSSION
Several issues arise with millimeter wave beaming, especially for retail beaming. These are summarized as follows.

(1) Low efficiency of generation and transmission. The answer here is twofold. First, even if the efficiency is low, the net result should be compared to the value of the first watt-hour and first watt of capacity. The opportunity cost of waiting for the wired grid should also be considered. The second part of the answer is that net end-to-end efficiency using millimeter wave beaming is not low when compared to other power transmission options, and the efficiency is rising with research and development due to strong market interest in millimeter waves.

(2) Expense of solid-state arrays versus photovoltaic arrays. The answer is to design for synergy. Photovoltaic panels can be modified to serve dual-use as millimeter wave antennae at night, or even to transmit excess power during the daytime. Integrated PV-millimeter wave chips to receive, convert, and transmit power could provide a mass-market solution.

(3) Atmospheric propagation losses. This is a strong argument for minimizing the horizontal path at low altitude. Horizontal propagation should be conducted at high altitude, using aerostats or stratospheric platforms as far as possible. Options such as burn-through using different frequencies or evaporation ducts should be explored. The possibility of using waveguides through tethers to aerostats floating above the cloud layer offers an exciting possibility to break through this fundamental problem.

(4) High beam intensity. With small receivers, intensity will be high. It is standard practice to have a pilot beam position sensor and automatic cutoff that prevents transmission unless the link is functioning properly. The high intensity obviously poses issues with horizontal beaming at low altitude.

(5) Health effects of millimeter waves. This is a large and serious issue. So far, there are no known ill effects. However, not much research has been published, and long-term phenomena remain to be understood. Ryan et al. [2000] have reviewed health effects of millimeter waves. Millimeter wave energy is deposited within the first 1–2 mm of the human skin. This effect was used to therapeutic advantage in skin disorders, gastric ulcers, heart disease, and cancer in the erstwhile Soviet Union. The advent of so-called nonlethal crowd control weapons employing 94 GHz waves shows clearly that the heating effects of millimeter waves should be examined carefully.
(6) Infrastructure. One option to explore is to use the mobile telephone infrastructure as convenient last-kilometer transmitters or relays. In India the railway infrastructure has been traditionally used as the path for communications infrastructure to expand throughout the nation. The mobile telephone network is no exception; it has also spread along the railways first. Hence it is reasonable to expect that the retail power beaming infrastructure can in turn use the mobile phone infrastructure.

5.1. Atmospheric Propagation and Burn-Through

Du Bosq et al. [2008] have surveyed millimeter wave effects on other substances such as soils. Sharma [1974] reported on a 3-year study of the effects of refractive index, rain, humidity, and sea-breeze on the momentary fadeout of microwave signals in the tropics. Indian Railways has accumulated extensive experience with microwave line-of-sight transmission along the railroad right of way [Chakraborty 2009; Dalela et al. 2008]. Solar photovoltaic powered microwave repeater systems are used, where railway signals are transmitted between wireless towers [Sreekanth 2003]. 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 [Reddy and Reddy 1992]. This should give pause to anyone who believes that using microwave frequencies below 10 GHz guarantees high-efficiency, all-weather transmission. Farinholt et al. [2009] 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 (1 W), 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.

5.2. Phase Nonuniformity and Atmospheric Turbulence Effects

One criticism of millimeter wave and laser beaming coming from the proponents of low-frequency microwave beaming is that extreme mirror flatness is required. It is argued that if such perfection were feasible, the state of astronomical imaging would be greatly advanced from its present state. However, this argument misses several points. Firstly, low-frequency microwave beaming systems require a very large product of transmitter and receiver diameters, for any significant distance. Most such systems are sized for only 84% reception, that is, only the main lobe, because of the cost of building or installing antennae large enough to capture the first side lobe. This single reality more than neutralizes the claimed dry-atmosphere transmission advantage of low microwave frequencies. Most experiments to-date have used transmitter-receiver combinations that yield single-digit efficiency values. Atmospheric turbulence, refractive index gradients, dust, and interference with secondary reflections from the spilled radiation all conspire to produce considerable phase noise and other nonuniformities. Hence the first conclusion is that low microwave frequencies also suffer large amounts of noise and spatial nonuniformity.

This problem is not without solutions. In the Boost-Phase Intercept (BPI) problem of strategic missile defense, one pacing issue in the 1980s was the computer speed required to compute the spatial transfer function between the low-level pilot signal sent from the weapon and its reflection received from the target. The transmitter array would then be adjusted to compensate for this transfer function before the main high-power pulses were sent, so that the beam hitting the target would have the desired spatial characteristics and coherence. This option sounds exotic if done with
servo motors and mirror deflectors. However, consider that solid-state millimeter wave power beaming and reception will probably be done with large arrays of integrated converter/transmitter/receiver modules, each of which is a digitally-controlled device. Thus, tailoring phase and other characteristics is fundamentally possible at a single-device level. Once developed, this technology brings astronomy-quality electro-optical correction to mass-produced devices for the consumer market, and hence its development cost will be quickly recovered. Actual implementation of this and the other advances postulated before is of course a nontrivial endeavor, which is the reason for this article.

6. CONCLUSIONS

The state of present research related to retail power beaming appears to be as confused as our initial presentation of the diverse streams of enquiry relevant to this field. Systematic classification is hindered by the fact that ideas used in one paper for a given application offer excellent potential in other aspects of the power beaming problem. This is mostly attributable to the relative obscurity of the retail power beaming application. The technology is primarily being driven by the market for communication devices or military/security/astronomical imaging applications. However, for the same reason, there are several streams of technology that offer excellent promise when integrated towards power beaming. The reasons why millimeter wave bands must be explored for power beaming are laid out in the article. The use of millimeter wave bands, particularly in the 220 GHz atmospheric window, appears to be much more near term than was previously suspected, since 220 GHz components and fabrication technology are already being widely used in device development for other millimeter wave regimes. Direct optical conversion and various forms of opto-electronic technology appear to offer the potential to enable power beaming at high levels, far beyond what is presently considered for short-range or imaging applications. In particular, concepts such as the micro-resonators and waveguide bundle resonators offer intriguing possibilities. Some specific conclusions from the article are enumerated next.

(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 tethered aerostats, or stratospheric platforms, and a Space Power Grid constellation are considered. The aerostat offers small receiver size for retail exchange, while the stratospheric platform enables use of very small retail receivers when used as relays of power beamed from space.

(3) For low-altitude beaming, the 94 GHz band may be best suited, while for the stratospheric platform and Space Power Grid, the 220 GHz window is most suited.

(4) Synergy with cellphone and railway infrastructure offer immediate paths to establishing retail power beaming.

(5) Large arrays of solid-state MMICs offer the potential to integrate receiver, converter, transmitter, beam steering, frequency selection, and antenna phase correction possibilities. 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. With a few generations of cost reduction through efficiencies of scale, beamed power systems may be largely automated and achieve competitive cost effectiveness.

(6) Retail beaming technology offers a path to integrate direct conversion of solar power. 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.
Indian village electrification offers an opportunity to establish a retail beaming infrastructure with a growing fleet of stratospheric platforms.

Low efficiency and weather issues are not show-stoppers for retail millimeter wave power beaming, but new solutions such as waveguide beaming to and from aerostats, with horizontal wireless beaming between aerostats, may greatly increase end-to-end efficiency.

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