Policy Issues for Retail Beamed Power Transmission

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Abstract - **This paper discusses the interaction of technology and policy in enabling widespread rural access to clean solar electric power using retail delivery of beamed power. Recent advances in power beaming have made it possible to deliver electric power to off-grid locations using millimeter-wave beams and compact, efficient transmitters and receivers. The research question is how to bring about the public policy initiatives needed to enable widespread adoption of this clean and sustainable contribution to meeting energy needs. It is seen that this question leads to synergy between three national priorities: (a) the campaign to control global climate change, (b) the drive to improve air quality, and (c) the need for increased availability of energy for development. A benefit of the Beamed Power approach is that retail power transfer using beamed power will facilitate the realization the National Energy Technology Laboratory of the United State's vision for the modern grid.**

I. Introduction

The prevailing electrical power system is based on a relatively small number of very large utility-scale power plants, serving given areas in a hub-and-spoke arrangement. Grid interconnection between these large plants, and multiple paths to each customer group, serve to smooth out fluctuations and provide backup. Distributed generation (DG) systems on the other hand, have a larger number of generators located much closer to their customers. DG encounters several technical, economic and regulatory hurdles. A special reason for regulatory barriers is that the grid has to handle the fluctuations as these individual generators come on and off – and can suffer severe damage otherwise. Grid operators are forced to ensure that there is sufficient backup capacity to smooth over the sudden dropout of DG sources. This imposes steep costs on the grid. There is also concern about the liabilities for damage to other systems connected to the grid, due to the actions of individual DG operators. The new Federal "Smart Grid" initiative seeks to alleviate these problems through technology and policy, and make DG more viable, in order to facilitate connection of small renewable energy systems. In this paper, we look at the implications for incorporating beamed power, rather than power sent through fixed cables, in this new context.

Currently, most electric power on Earth is transmitted using wired power transmission systems. In this system, electrical power is transmitted from the source of power generation to the point of power consumption through an appropriately shaped conductive material. The wired method of energy transfer has various disadvantages:

1. Large infrastructure is required for transfer of power using conventional wired grid transmission.
2. Land areas and right-of-way required for transmission lines.
3. Damage to ecosystems, most evident from the swaths of forest cleared to keep power lines free from tree limbs.
4. Wired power transmission is highly susceptible to attacks and accidents.
6. Wired power transmission systems require high maintenance, and are highly susceptible to outage due to wind and ice storms.
5. The conventional grid is not conducive to micro-renewable energy resource exploitation since wired power transmission is only cost effective over long distances.

To counter the disadvantages of wired power transmission, Beamed Power Transmission ([2][3][11]) can be used. Beamed (wireless) power transmission uses electromagnetic radiation (microwave or lasers) for power transfer. First demonstrated in 1897 by Nikola Tesla using radio frequencies, and using microwaves in 1964 (Brown, 1992), wireless transmission was extended to tens of kilowatts by NASA in 1975. In the 1980s, beams of up to 1GW were considered (and possibly demonstrated) under the Strategic Defense Initiative (aka "Star Wars"). The concept of bringing solar power from large satellites in space or on the Moon, have been explored since the 1960s, both in the USA and outside, notably in Japan. These concepts have generally been stymied by the very large infrastructure needed to convert and transmit microwave beams over very large distances.

On the other hand, there has been a revolution in the use of wireless transmission of information. Satellite television, cellular telephones and wireless internet connections are the best-known examples, and these together comprise a very large marketplace with billions of customers. These clearly involve beamed transmission of electric power, but the intent has been to transmit information encoded in the beams, rather than power itself. Communication satellites send out fairly narrow beams, but the 10,000 to 36,000 kilometer distances from earth to their orbits means that generally, the beam is spread out and covers a large area when it reaches Earth's surface. The emphasis in this market has been to continually reduce the amount of power needed to ensure a clear signal, and this effort has received a major boost with the advent of digital high-frequency transmission and reception. Thus there are already billions of devices operating every day, that have the capability to receive electromagnetic waves and decode the information contained in them with extremely high rates of processing.

Can similar technology be applied to transmit power to individual devices? The answer is certainly positive, and the idea has been tried out in several applications. Where the intent is to deliver very small amounts of power to micro-devices to perform valuable functions, it is acceptable to beam the power over a significant area, inside which all devices can accept whatever power falls on their collectors, the rest being wasted. This notion has been used in Japanese concepts to beam power over urban areas where there are large numbers of customers, automatically keeping their electronic devices charged. One Japanese concept has taken this approach to the other extreme. A demonstration project under "SPS2000" proposed to have a kilometer-sized solar cell array in low Earth orbit, converting solar power and beaming it over a wide swath of equatorial land, covering many forested and less-developed areas. The idea was that governments in these areas would be happy to provide funding for this, since it would allow residents to use small collectors to obtain enough power to keep their batteries charged, to operate critical electrical equipment. Again, most of the beamed power would go waste, so that the efficiency of the process is extremely low.

To do better, one must be able to capture most if not all of the power in the beam, which implies very tightly focused beams and well-aimed receiver-transmitter links. This raises a host of new issues relevant to policy discussions.

Chowdhary and Gadre studied the Beamed Power Transmission System (BPTS) (5) to see how to synergize its various attractive features with the needs and opportunities in rural communities and farms. In this paper, we describe the public policy aspects of this research.

BEAMED POWER TRANSMISSION SYSTEMS (BPTS)

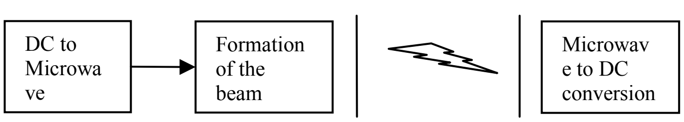

Figure 1: Schematic of a DC to DC beamed power transmission system

The BPTS has the following main components:
1. A DC to microwave power conversion unit,
2. A transmitting antenna that forms the beam,
3.A receiving Rectenna (rectifying antenna) that receives the beam and converts the beam to DC power.

The transmitting antenna converts DC current into a microwave beam. Brown [2] suggests the use of devices similar to standard microwave magnetron technology with external passive circuitry for creating a phase steerable transmitting antenna as a low cost conversion system.

A Rectenna [2] is a device that has been specifically designed to convert microwave energy into electrical energy. The Rectenna combines the functions of an antenna and a rectifier. A rectenna could be made directional by arranging its elements in a multi element phased array.

Attractive features of BPTS include:

1. Cost effective over a short distance: This motivates the use of BPTS for micro-renewable distributed energy generation schemes and local sourcing of energy.
2. Low material and infrastructure demands. By eliminating the need to use wires the BPTS considerably reduces the raw materials that are needed to put the system in place.
3. Low land footprint.
4. Relatively low maintenance, and far better access for maintenance. All the maintenance is at transmitting, relay and receiver stations, compared to the need to inspect and maintain thousands of kilometers of transmission lines through forests, tunnels, mountains and fields.
5. Less susceptible to attacks and accidental power outage: Since no wires are involved, the risk of power loss due to severed wires is eliminated.
6. Easier to incorporate "smart" technologies: Automatic fault diagnosis and fault tolerance, advanced communication with end users, and rapid adaptation to varying demands become feasible. Phased directional arrays that require no moving parts make it extremely easy for the BPTS to be modular and flexible. The use of microwave band transmission signals makes it easier to embed information in the transmitted power. The modularity afforded by independent transmitting and receiving units makes fault diagnosis and fault tolerance as well as changing the grid topology relatively easy.
7. BPTS is conducive to NETL's Vision of the Modern Grid: The National Energy Technology Laboratory of the US has put forward a vision for the new US grid infrastructure [5]. Under this vision the modern grid is expected to be sufficiently flexible to handle distributed energy generation both at large and small scale. It needs to be reliable and robust against attacks. It needs to be self-healing, and it needs to have integrated capability of communicating with users. Furthermore, the modern grid needs to be "green", that is, there should be a minimum waste of material and emission of hazardous byproducts in its construction and maintenance. BPTS provides ideal solutions for these issues.

BPTS has the ability to serve various unique requirements that are currently ill satisfied with wired transmission:
1.Rapidly provide power to remote outposts without having to setup expensive wired architecture or without having to carry power generation capabilities.
2. Connect moving power generation platforms with the main grid.
3. Scaled BPTS receiving systems can be used on the

battlefield by independent rapid deployment units and light infantry for instant access to power.

4. BPTS can be used to provide power to a number of electronic devices (including miniature robots) within a field.

PUBLIC POLICY ISSUES

However, the use of BPTS for power transmission raises a host of Public Policy Issues. These include:

1. Ensuring safety
2. Education for safe use and removing misconceptions (such as superstitions regarding cooked chickens etc),
3. Frequency band allocation
4. Security / ITAR issues of beamed power technology
5. Land co-use
6. Line-of-sight / airspace access issues
7. Policies to encourage synergy between global warming control policy, renewable power generation, agriculture, and technology development issues.

Safety

Microwave radiation falls in the non-ionizing part of the radio wave spectrum [10], in fact the microwave frequencies fall below the frequencies of visible light. Measuring radio frequency is accomplished by measuring power density of the radio wave field and is measured in miliWatt/cm2. Microwave radiation, which is non-ionizing in nature, does not cause fundamental molecular changes in the structure of subjected biota. However, certain frequencies of microwave radiation may excite, directly or through harmonic multiple frequencies, excite water or other molecules, causing heating. Prolonged exposure to high intensity microwave radiation at such frequencies will cause tissue damage including severe irreversible burns. The current OSHA standard for safe microwave radiation exposure for humans is $10 mW/cm^2$ over any possible 0.1 hour period. The following relationship can be used to determine the power density at the center of a receiving antenna [2].

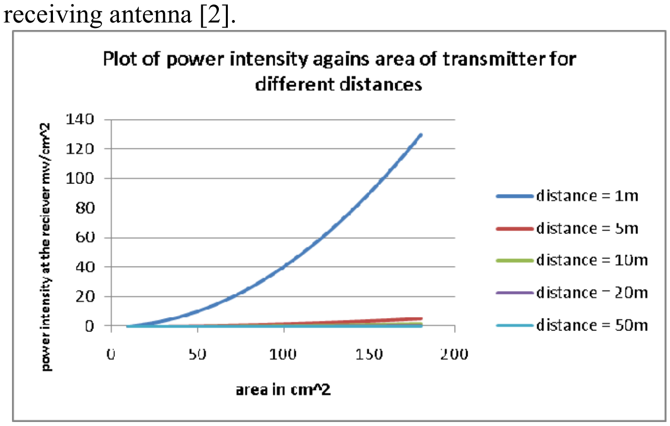

Figure 2 Plot of Power Intensity against Area

where PD is the power density at the center of the receiving antenna, Pt is the total radiated power from the transmitter, At is the area of the transmitting antenna, λ is the wavelength used, and D is the separating distance between the two apertures.

Water heating is not the only danger. Certain microwave frequencies also interact with metals (example: steel foil in microwave ovens) and can be used to melt certain dielectric materials. The 80-90 GHz band is used in military devices that cause intense pain due to interaction with the outer skin layer (claimed to cause no permanent damage) but at higher power levels, such devices have been blamed for deaths. Further study is warranted on the acceptable exposure to microwave radiation to biota in sparsely populated and open areas when targeted beams are used. On the other hand, there is a vast experience base with using microwave transmissions, and safe long-term use has been established for various frequency bands, for very substantial power levels.

Since transmission stations should also comply with the requirements on safe microwave radiation exposure, we will assume that the power intensity at the transmitter is Pt = 10mW/cm2 and vary the other design parameters to arrive at an estimate on the efficiency. Figure 2 plots power intensity at the center of the receiver for different areas and varying distances for the fixed OSHA approved transmission power intensity (Pt = 10mW/cm2), and a wavelength of 5mm. The total power of the transmitter (Pt) is calculated by multiplying the power intensity of the transmitter by its area which is assumed to be the same as that of the receiver. It is to be noted that this is an aggressive estimate of the total power available, as the transmission power intensity could be significantly lower to the sides of the transmitter than in the middle. From this plot it can be seen that the intensity of the power seen at the receiver drops dramatically as the distance between the two apertures increases above 1m. The power density ratio between the transmitted and received powers drops below 0.01 as the distance increases above 20m and an increase in area is not sufficient to change this by much. From this discussion the following constraints are exerted:

1. If power is to be beamed in densely populated areas such as workplaces, or homes, then in order to meet the OSHA guidelines and still keep the efficiency up the distance between the receivers and the transmitters must be minimized.

2. If the power is to be transmitted over long distances then in order to keep the efficiency and still meet the OSHA guidelines on exposure to microwave radiation the wavelength will have to be significantly reduced. This will cause issues with atmospheric attenuation and transmission through obstacles.

3. The ideal situation for BPTS for long distance transmission would be to operate at higher power intensities than specified by the OSHA guidelines. This can be achieved by placing the receiver and the transmitter in sparsely populated areas. A very acceptable alternative is to have foolproof switches controlled by a very low intensity, eye-safe beam, whose interruption instantly cuts off the main power beam.

Interference with Existing Devices

The following table lists the frequency spectra that are commonly used by various devices that are close to microwave frequency range (0.3Ghz to 300Ghz):

Table 1: Frequency ranges in the microwave spectrum used by common services and devices

Device or Service	Frequency range used
Cellular phone	824-850 MHz
Air Traffic Control	960 – 1215 MHz
Global Positioning System (GPS)	1.227 and 1.575 GHz
Deep Space radio communication	2.29-2.30 GHz
Standard Wireless Local Area Networks (WLAN)	2.2-2.7 GHz

It is important to note that the GPS signal is highly susceptible to noise, and it is often noted that GPS signal detection next to a WLAN receiver is often lost. Microwave ovens when in use can significantly deteriorate the performance of WLAN networks. The difference is significant enough and felt directly by the user of the network. It is clear that microwave radiation of 2.4 GHz will produce some amount of interference with WLAN devices, and perhaps also Cellular phone service. These effects need to be better studied. As a conservative design option, it could be better to steer away from any frequency that is otherwise used. However, one should note that narrow-beam transmission and collection, that only occurs when the receiver and transmitter are perfectly aligned, and tolerate little spillage, ensure that there is little power scattered to interfere with other devices.

On the other hand, higher microwave frequencies are susceptible to attenuation due to water and other atmospheric gases. Conservative thought suggests that at 2.Ghz the atmospheric attenuation is at a minimum. This explains why the 2.4 GHz microwave frequency is ubiquitously used. However, due to the issue of interference, it might be beneficial to move to higher frequencies and lower wavelengths. Koert et al. in [11] discuss the design and development of a 33 GHz rectennas and transmitter systems for the beamed transfer of power from ground to a high altitude aircraft. By using 33-40Ghz microwave radiation (Ka band radiation) it is possible reduce the size of the transmitting antenna by a factor of 14 (from 634 ft diameter to 44 ft diameter), which is significant. However, Ka band radiation is susceptible to attenuation due to rain which will pose issues with robustness. In [1] Chowdhary and Gadre noted that for frequencies greater than 10 GHz the attenuation due to rain is about 10dB/km. At such high attenuation levels the receivers and transmitters would have to be placed relatively closely if frequencies greater than 10 GHz are used.

In summary, we have that the following considerations based on frequency constraints:

1. Frequencies greater than 10 GHz could mean smaller antenna size and lower interference with ground devices.
2. Higher frequencies could suffer higher susceptibility to attenuation due to rain and humidity.
3. Most parts of the world (except tropical climates) see a fairly low amount of rain time. If a BPTS is designed to use high frequency (Ka band) microwave beams, then the occasional drop in efficiency in signal transmission must be accounted for.
4. For solar energy transmission purposes, this should present minor problems, since most solar energy systems will not function in rain, and in either case a buffer could be provided by providing onboard storage facility in the micro-renewable energy generating units.
5. The biggest challenge is when BPTS must compete with the reliability of the conventional wired grid. In these situations an active control system which controls the signal intensity in order to compensate for atmospheric changes can be designed.

Ball [12] reported experiments to determine what frequencies of the microwave spectrum are attenuated due to the presence of water vapor. Ball reports that previous estimates of atmospheric attenuation due to water vapor could have been pessimistic, and that at higher frequencies such as 33-40GHz the atmospheric attenuation could be as low as that at 2.4GHz. Clearly, further feasibility studies must determine the exact amount of atmospheric attenuation seen when using different high intensity frequency bands for power transmission. Signals traveling horizontally through the earth's atmosphere are susceptible to higher levels of attenuation than signals travelling from space to the surface of the earth.

Financial Feasibility

Chowdhary and Gadre studied in detail the feasibility of BPTS for commercial use in [1]. They have proposed an approach to a scalable BPTS to increase commercial viability. They use a frequency of 90Ghz to exploit the low attenuation due to water vapor at that frequency.and propose the use of a relatively large (~20 m diameter) effective antenna aperture to be used for high intensity, long range power transfer, and a relatively small and light weight (~0.6 m diameter, ~ 1.5 kg) effective antenna aperture system that can be use on moving platforms and perhaps carried by humans (soldiers).

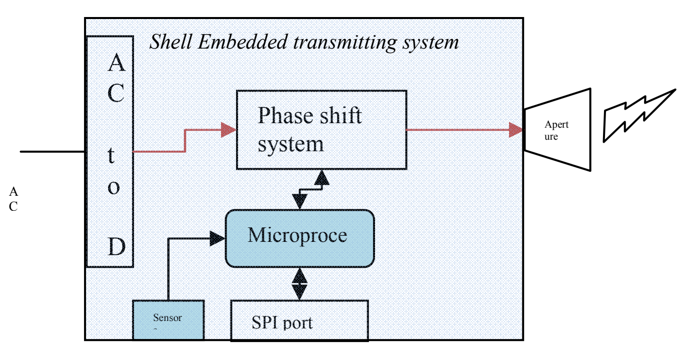

Figure 1 Schematic of shell systems components and their interdependencies

Public Education:

Significant misunderstanding related to microwave energy radiation is ubiquitous in the common public. Any significant progress made towards a BPTS will be hindered by such misunderstanding. It is suggested here that third party studies be conducted on the effects of high and low intensity microwave radiation in the range of 90Ghz. The results of this study should be made publically available.

Encouraging Entrepreneurial Development:
This paper has described the significant advances BPTS can afford in fulfilling NETL's vision of the modern grid. Advancement in BPTS is of great consequence to the US military as it allows rapid deployment of power to remote outposts and even to individual units operating the field. To that effect, it is suggested that this topic of research should be considered for Small Business Innovation Research (SBIR) program run by the armed forces and other government organizations (NASA, NSF, Department of Homeland Security etc.). University research can also be encouraged through the government's Small Business Technology Transfer (STTR) program.

Incentives for using BPTS:
BPTS is conducive to the development of small scaled micro renewable energy resource exploitation as it negates the need for developing expensive wired energy grids. It is suggested that incentives in the form of green credits should be afforded to entities using small scale micro renewable energy resources for power independence. It is further suggested that incentives should be given to such entities to transmit any excess power through a BPTS to the local grid.

Protection of National Interest:
BPTS systems provide an efficient tool for providing power to units of the armed forces operating in remote locations on the battlefield. On realization, this technology has the potential to provide sufficient power to any field unit without having to carry independent power source. It would be natural to protect such technology through ITAR restrictions. However, it should be noted that given the current economic scenario, and the fact that delivery of energy is a global problem, significant global collaboration will be required for development of BPTS. Allowing for global cooperation without threatening national interest is a significant policy issue that needs to be addressed early on in the design.

Pathway to Retail Beamed Power through Public Policy Initiatives

Significant government involvement will be needed to mature the complete potential of this high risk technology. Based on increasing technological risk, the required policy initiatives can be roughly separated in the following levels:
Level 1: Encourage small scale private sector innovations relying on beamed power by recognizing the environmental benefits.
Level 2: Encourage public – private sector large scale projects that use direct beamed power for powering subsytems.
Level 3: Encourage large scale augmentation of retail wired power systems with beamed power.

It is suggested that policy initiatives should be created that encourage the development of technology simultaneously on all three levels with financial support concentrated on level 1 in early stages and concentrated on level 2 and 3 in later stages. This allows for distribution of risk and gradual across the spectrum incorporation of the technology into main stream applications.

Case Studies

In this section we discuss some existing private and public initiatives around the world that use beamed power transmission for transfer of power or information.
PRIMOVE Catenary Free Technology:
Bombardier PRIMOVE [16] is a system for transferring power without physical contact to tram (urban rail) systems operating in urban environments without the need of having overhead catenaries. The system relies on underground DC electric field that is only activated on the section of the track on which the tram is currently overhead. A pickup coil (rectenna) located underneath the tram body converts the electromagnetic field into DC current. The PRIMOVE system is a great example of a system that can be implemented with current state of the art technology. Since the pickup coils are located very close to the DC beamed power source, the efficiency achieved can be very high. Since the pickup coils are located underneath the seats, it is possible to design for providing adequate shielding to satisfy any government requirement for allowable microwave radiation exposure. By removing overhead catenaries, the PRIMOVE system allows for cost saving and decrease visual pollution. PRIMOVE allows a company like Bombardier to have a market advantage and develop eco – friendly technologies without risking development on a product that may run into policy issues. PRIMOVE is an example of technology that needs to be supported through policy initiatives in order to allow for a pathway for beamed power transmission technology development in the private sector. This case study is an example of level 1 policy initiatives in encouraging retail microwave power.

Indian Railway Microwave Communication System:
Indian railways employs microwave communication towers for communicating the position of trains using on track sensors. These towers are currently powered off the wired grid while some of them come equipped with solar arrays. There is a strong potential for further development by powering some of the towers with beamed microwave energy transferred using the same architecture. This is an example of an existing project which can be used as a launching pad for technical innovation in this field through government – public sector cooperation. This is an example of Level 2 policy initiative.

Space Power System
Space Power Systems use the abundance of sun light in space to generate solar energy and propose the use of beamed power to transfer the generated electrical energy to earth [3]. Beamed

power from space will be a key element of this technology. Japan has been on the fore front of this technology in terms of policy initiatives. According to *Nikkei,* a leading Japanese news paper, the Japanese government has already asked for public-private sector partnerships to be formed and initial satellites to be launched by 2015. The Japanese government is pushing for a 2030 deadline for having space power projects operations. The Japanese government has an official space power program in place in the JAXA Aerospace Research and Development Directorate. This is an example of strong support from government for encouraging entrepreneurial development in high risk technologies. This is an example of a level 3 policy initiative.

CONCLUSIONS

In this paper we proposed a retail BPTS as a viable and cost effective alternative to wired power transmission grids. We showed that BPTS are conducive to meeting NETL's vision of the modern grid. Our study also indicates that BPTS is also conducive to the development of micro energy generation units exploiting micro renewable resources. It is suggest that incorporation of BPTS should be in an incremental way with BPTS initially intended to augment current national grid, with intentions for scaling up.

Spare text:

There is a strong drive in the market towards using smaller self sufficient units that generate sufficient electricity for local purposes. This paradigm is termed as distributed energy generation. It is postulated that distributed energy generation will not only be able to support our ever growing energy needs, but it has the potential to be extremely cost effective and sustainable since it is primarily based on exploiting renewable resources.

Given the large needs for energy in agriculture, farms were identified as ideal locations to receive retail beamed power from spacecraft, aircraft or other transmitters / relays of power from renewable power plants.

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