
Andrew Bomber
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Professor La Rosa
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Abstract

Wireless power transmission is an underdeveloped field of study. There are many promising applications for the ability to transport power over great distances and boundaries without the need for transmission lines. Current technology employs the use of microwaves because of the economic and energy efficiency that can be leveraged by products already in production. There is some effort to develop new technology that would accommodate propagation by electromagnetic waves in and around the visual light spectrum; however those technologies are just emerging.
Introduction

The area of wireless power transmission is very interesting. The technology is in its infancy but the overall benefits from its maturation could be significant to society as a whole. World population is expected to continue to grow exponentially. Five sixths of the world’s population lives in developing nations. Most developing nations such as China, India, and Pakistan are rapidly improving their standard of living. All of these trends point to an energy demand that will grow at even a larger rate. Wireless power transmission could one day allow us to generate solar power on a satellite and beam it down to Earth, transmit power to a water treatment plant for a disaster relief operation or power a flying communication relay station from a terrestrial station. There are a few engineering hurdles yet to overcome to make this technology viable to today’s investors, but with the rising demand for energy and the rapid improvements being made it is just a matter of time before wireless power transmission becomes an industry of its own.

Figure 1. Projected yearly growth in world energy consumption. (3)
History of Wireless Power Transmission

The discussion of wireless power transmission as an alternative to transmission line power distribution started in the late 19th century. Both Heinrich Hertz and Nicolai Tesla theorized the possibility of wireless power transmission. Tesla demonstrated it in 1899 by powering fluorescent lamps 25 miles from the power source without using wires (1). Despite the novelty of Tesla’s demonstration and his personal efforts to commercialize wireless power transmission, he soon ran out of funding because it was much less expensive to lay copper than to build the equipment necessary to transmit power through radio waves.

William C. Brown contributed much to the modern development of microwave power transmission which for many reasons dominates research and development of wireless transmission today. In the early 1960s brown invented the rectenna which directly converts microwaves to DC current. He demonstrated its ability in 1964 by powering a helicopter from the solely through microwaves.

“In 1982, Brown (Raytheon) and James F. Trimer (NASA) announced the development of a thin-film plastic rectenna using printed-circuit technology that weighed only one-tenth as much as any previous rectenna” (2). This new, lighter weight rectenna led to the development of the Stationary High Altitude Relay Platform (SHARP). The purpose of the sharp program, as its name suggests, was to develop unmanned aircraft that would maintain a circular trajectory above a microwave antenna field for the purpose of relaying communications from various
ground terminals. No commercial development past the prototype stage has been funded.

Despite these advances wireless power transmission has not been adopted for commercial use except for the sole exception of pacemakers and electric toothbrush rechargers. However, research is ongoing because of the many promising applications suited for wireless power transmission.

Applications

Due to the relatively low cost and high efficiency of power line transmission, wireless power transmission is only practical under two general circumstances: 1) In order to transport necessary power over an impossible or impractical barrier for wires or 2) Rapid deployment of assets for disaster recovery or military operations that could be aided by wireless power transmission more than by local generators. For that reason most research is focused on applications that solve one of these two problems.
Solar Power Satellites (SPS)

The most widely documented area of research is being done with the goal of putting solar power generating satellites into space and transmitting power to Earth stations. The idea was first proposed in 1968 and all of the experiments thus far have only been carried out in terrestrial laboratories.

Figure 3 Proposed SPS satellite system (5).

The SPS satellites would be put in high earth orbit at geosynchronous locations. The high orbit would allow them to receive light 99% of the year (5). A large rectenna array facility will be built on the Earth to collect the incoming microwaves. In order to maintain a good lock on the rectenna the satellite will need to be built
with a retrodirective transmitter which locks on to a pilot beam emanated from the
ground station.

Since most of the research is done in the 2.4 GHz to 5.8 GHz range there are
some spectrum regulatory issues to deal with. Also since the retrodirective antenna
system is unproven. There is the health concern that the microwave beam could
veer off target and microwave some unsuspecting family. However, a Japanese
government agency is planning to send up 10 to 100 kW low earth orbit satellite to
prove its feasibility. (4)

Current Technology

The driving force behind system design is the overall system efficiency. The most
current research and proposals use microwaves as the frequency range of choice
for transmission. As you can see from figure 3 that 54% efficiency is currently
attainable and 76% is possible using current technology for microwave power
transmission. Lower frequency waves would be hard to direct because of their
large wavelengths. For transmission efficiency the waves must be focused so that
all the energy transmitted by the source is incident on the wave collection device.
There is a lot of practical experience with directional propagation of microwaves
from the communications industry. Higher frequencies are also impractical
because of the high cost of transmitters and the relative low efficiency of current
optical and infrared devices. Bare in mind that when I talk of low efficiency I am
speaking of low efficiency in energy transfer, not intelligence transfer. The fact that
there is a lot of practical experience with microwave technology also makes it cheaper to produce instruments associated with microwave transmission and reception.

The most common transmitters for microwaves are the traveling wave tube (TWT), klystron and magnetron. The TWT is far too expensive and power restrictive making it impractical for the task of power transmission. The klystron has been the DC to microwave converter of choice however it is also somewhat expensive. Many researchers are looking to use magnetrons instead because they are cheap and efficient. Magnetron frequency output is not as precisely controllable as the klystron or TWT but power transmission is more lenient to frequency fluctuations than communication systems are. One of the more common proposals would be for an array of magnetrons to be used as the transmitter. One of the main advantages to using many smaller magnetrons as opposed to a few klystrons is that 300 W to 1kW magnetrons are already mass produced for microwave ovens. The efficiency of magnetrons is inconsistently

![Figure 4. Breakdown of Microwave power transmission efficiency. (5)](image)
reported. Some sources put the magnetrons efficiency at 85% to 95% where as it is known that microwave ovens tend to have an efficiency of around 65% to 70%.

The receiving device in most proposals is the rectenna. The rectenna is an array of rectifying devices that convert electric field into DC current. The original rectenna was simply an array of Schottky diodes. There are a number of papers out on various modifications to the original design to include circularly polarized rectennas which may prove helpful in combating the Faraday Effect on microwave transmissions from an SPS satellites.

Figure 5. Diagram of basic rectenna.
Emerging Technology

There are some obvious questions to be posed about the SPS system. One of these questions is, "Why go to all this expense? With such a large a patch of real-estate would it not be more practical to put a solar cell farm in the same location?" the answer to this question is simply a matter of efficiency. As you can see by Figure 3 Proposed SPS satellite system (5). the efficiency for a wireless power transmission system is determined by the product of the efficiency of all the systems subsystems. Currently microwave transmitters and receivers are much more efficient in addition microwave components are already in mass production so these systems are also more cost efficient. Electro magnetic waves in the visible light spectrum are less likely to be absorbed or scattered by the Earths atmosphere. so in principle if an optical system could be developed then the system would be more efficient when it comes to free space transmission. For that reason there is some research ongoing into the feasibility of optical systems for power transmission. The development of better photovoltaic cells or an optical rectenna would also advance the practicability of optical power transmission.

In order to improve the cost and energy efficiency of the transmitting system Physical Science Inc. is researching the possibility of using ytterbium fiber laser with 64% efficiency for wireless power transmission (7). This efficiency is not quite at the level of a magnetron but with improvement it might become good enough to make the optical system as a whole more efficient if a more efficient receiving element is developed.
According to the Department of Energy's National Center for Photovoltaics, modern commercially available single cell photovoltaic panels are limited to an efficiency of about 25%. Every photon incident on the cell that is

![Figure 7](image)

Figure 7. Photons with lower energy than the band gap pass through the cell. A photon with energy equal to or greater than the band gap creates an electron hole pair which creates current. Any the difference in energy between the photon and the band gap is lost as heat.

According to the Department of Energy's National Center for Photovoltaics, modern commercially available single cell photovoltaic panels are limited to an efficiency of about 25%. Every photon incident on the cell that is
larger than the band gap creates one electron hole pair, which is the source of the DC current. Any difference in energy that is larger than the band gap is lost as heat and not captured as current. Any photon with less energy than the band gap is passed through the system without collection.

Figure 8. There are two proposed methods for Multijunction PV cell design. The first is called the spatial technique and it is intended to separate the light into different frequencies that would then come in contact with the appropriate PV cell for that frequency. The second idea was to stack materials one on top of the other with increasing band gaps (6). Multijunction cells are also being researched. The idea behind a multi junction cell is that the higher energy photons will be collected first by a material with a larger band gap and that smaller photons will be captured by materials with smaller band gaps. This would reduce the amount of energy lost as heat and thus conserve more useful electric energy. Two techniques were developed for the multijunction
cell. The spatial technique aimed at separating the light with a prism so that the separated light would be incident on the most appropriate material for efficient light energy collection. The second technique of stacking the materials in order of successively larger band gaps proved more promising. There is too much room for error in the prism optics system whereby the higher energy light may be incident on a lower energy band gap material.

Current research into multijunction PV cells shows that greater efficiency at higher concentrations of light. This means that such devices would have improved efficiency when collecting energy from a concentrated source like a laser. (6)

![Projected real-world efficiencies for multijunction PV cells at a concentration of 500 suns](image)

**Figure 9.** Projected real-world efficiencies for multijunction PV cells at a concentration of 500 suns (6).

Optical rectennas are also being researched with a grant from the National Renewable Energy Laboratory (NREL), particularly at ITN Energy Systems, Inc. Their idea is to use a metal-insulator-metal (MIM) diode as the rectifying device in
a rectenna array. A rectennas frequency is determined by the spacing of the elements as the conducting contact acts as one half of a dipole. Their proposal states that simulations point to a possible 84% efficiency. However, experimental results thus far have topped out at 1% efficiency (8). Which makes this technology seem to be a distant possibility if not all together impractical.

Conclusion

Wireless power transmission is a promising area of study. The ability to transport power from a power generation facility on a satellite celestial body to Earth would help the human population keep pace with its energy demand. However, the most practical wireless power transmission system is too costly and underdeveloped to be employed today. Research will continue.
References

1) Wikipedia. (Updated: March 19, 2006) “Wireless energy transfer”
   Wikimedia Foundation, Inc.
   http://en.wikipedia.org/wiki/Wireless_energy_transfer

2) Cynthia Boyko & Stu McCormick. (Updated: February 6, 2001). by


   Power Transmission in Japan”. IEEE Microwave Magazine. December

   Transmission and its Application to Space” IEEE TRANSACTIONS ON
   pp. 1239-1250.

6) U.S. Department of Energy National Center for Photovoltaics (NCPV). “The
   Basic Physics and Design of III-V Multijunction Solar Cells “
http://sbir.gsfc.nasa.gov/SBIR/abstracts/04/sbir/phase1/SBIR-04-1-X2.03-9461.html

http://www.nrel.gov/docs/fy03osti/33263.pdf