Lunar Wireless Power Transfer

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ABSTRACT

This paper examines the feasibility of a multi-kilowatt wireless radio frequency (RF) power system to transfer power between lunar base facilities. Theanalyses show that wireless power transfer (WPT) systems can be more efficient and less expensive than traditional wired approaches for certain lunar and terrestrial applications.We already have the available technology necessary to make large solar arrays on the moon, and then use wireless power transmission via microwaves to send the resulting electricity back to earth. Although the upfront cost would be high, it wouldn't be impossible.

The study includes evaluations of the fundamental limitations of lunar WPT systems, the interrelationships of possible operational parameters, and a baseline design approach for a notional system that could be used in the near future to power remote facilities at a lunar base. Our notional system includes state-of-the-art photovoltaic (PVs), high-efficiency microwave transmitters, low-mass large-aperture high-power transmit antennas, high-efficiency large-area rectenna receiving arrays, and reconfigurable DC combining circuitry.

Keywords

Photovoltaic, Rectenna, Microwave transmitter, Rectenna array, stretched lens array, Load station.

INTRODUCTION

As we enter the new century, experts agree that the cost of power is one of the biggest barriers to worldwide prosperity. Most of the existing sources of power are based on resources that are being used up, such as coal and oil. In addition these resources are causing problems withpollution and possible global warming.

So even putting aside the politics of getting the oil for reasonable prices, as more people around the world use more energy, the current ways of making electricity won't meet the demands of the new century.

Earth based renewable energy sources have drawbacks too. Terrestrial renewable systems (hydroelectric, geothermal, ocean thermal, waves and tides) cannot dependably provide adequate power. Using wind power would require capturing one-third of the power of the low-level winds over all the continents. Earth based solar power is only available during the daytime, and it is always affected by the weather.Studies the World Energy Council has funded, show that earth based solar energy will be able to provide less then fifteen percent, of the electricity that will be needed for prosperity on earth, by that year.

The following ideas were illustrated for lunar solar power system.

- Build ten to twenty paired bases- One located close to the eastern visible horizon from earth, and the other close to the western visible horizon where up to one percent of solar power will be collected from...
- Fields of solar power arrays located on the back side of the moon five hundred to 1,000 kilometers past the edge we see. They will be connected to the paired bases on the side visible to earth by underground electric power cables.
- The electricity collected from the solar arrays will be converted to low intensity microwave beams and sent to a special type of antenna, called a rectenna, on earth.
- The rectenna will change the microwave power back to electricity and feed it to the local electric grid.

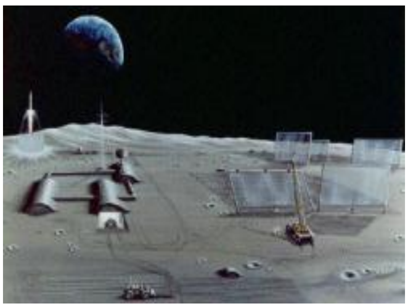

Fig. 1
Lunar Power Station at Moon

- The system would be capable of supplying the 20 TW (Terawatts) of power, or more, that arestimated to be needed by ten billion people in 2050.

NASA has embarked on a bold mission to return to the moon and establish a permanent presence. A moon base will require a vast amount of resources that can be extracted from various locations. A key question is how to deliver power to facilities (load stations) distributed on the lunar service, possibly in places where there is little sunlight. Initially, the load stations are planned to be 0.5 to 2km away from mountain-tops where photovoltaic generation stations can be placed. Each site is expected to require 10kW of power to operate.

Traditional power transfer methods for this type of off-site extraction mission would utilize cables. These transmission lines must traverse large distances, are sensitive to temperature, will be expensive to transport from Earth to the moon, may be a safety hazard for lunar operations, are susceptible to solar flare induced transient effects, have large diameters due to high voltages and power levels, have a large mass, and are difficult to manage due to residual cable stresses.

In addition, once the cables are set up, they would be difficult to move in the event that a different facility needs to be powered. Since multi-kilowatt power requirements are envisioned for these work sites, new methods of power transfer must be explored.

WIRELESS POWER TRANSMISSION SYSTEM DESIGN STUDY

3.1 Wireless Power System Requirements

The four key parameters identified for the wireless power transfer system design of interest are:

• Power must be beamed from four solar power generation stations to five fixed loadstations;

• Power received at each facility must be at least 10 kW;

• Load stations must receive power from minimum of two generation stations;

• Distance between transmitters and receiver ranges from 0.5 km to 2 km.

The beaming frequency, transmit and receive apertures sizes, and overall architecture are parameters varied in this study to show trends and the potential optimization.

This study considers the following system aspects of a wireless beaming system with respect to the specifications given above:

1. Top level system architecture – this includes a discussion of the distribution of power from 4 solar power generation stations to 5 load stations, as well as a high-level system block diagram.

2. Solar power generation – overviews the state of the art in PV arrays and discusses requirements in terms of size and mass for the required 50kW of received power at the five sites.

3. Power management and distribution – describes how the output of the PV arrays is managed and distributed to microwave transmitters.

4. System grounding on the lunar surface – electrostatic and other means is discussed.

5. Energy storage – describes alternatives and strategies for storage at the transmitter and site ends.

6. RF wireless power transmission – consists of a discussion of choice of frequency, transmitter technology, transmit aperture for given distance, towers for line-of-sight transmission, rectenna array size and DC reconfiguration. This is the central part of the study, but it cannot be considered properly without the other parts of the system.

7. System considerations including potential harm to astronauts and thermal issues are outlined for future more detailed study.

8. Mass and cost of the system is estimated. This is a very rough estimate since there is significant new work, and detailed analyses and design have not been performed.

OVERALL ARCHITECTURE

The overall architecture for the lunar Wireless Power Transfer (WPT) system is shown in Figure 2. Four transmission towers power a total of five load stations, such that each facility may be powered by at least two towers, and each tower can power up to three facilities. Each tower can send power in up to three directions using three separate microwave transmitting antennas. Each arrow represents a directional microwave beam. The distances between the transmitters and rectenna arrays are between 0.5 and 2km.

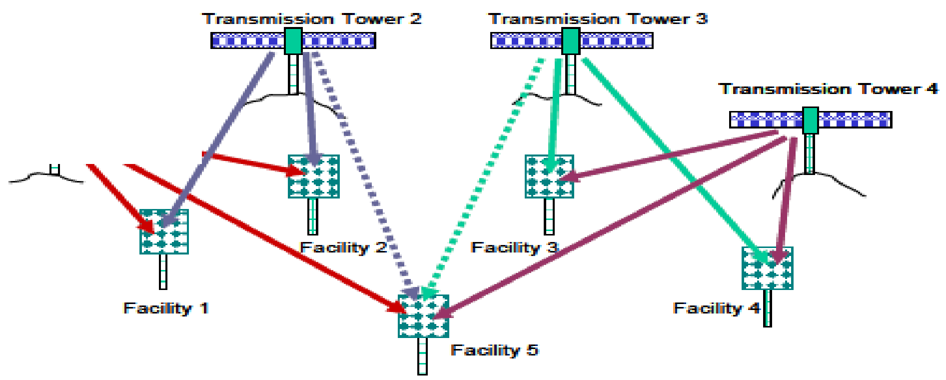

Fig. 2 Top Level Diagram of Notional Lunar Wireless Power Transfer System

Transmitter power levels contained in different beams is shown in table 1.

The most relevant parameter for comparing WPT with a traditional cable power transmission system is the overall efficiency and mass, with cost following.

Figure 3shows an overall system block diagram, with the relevant efficiency budget given for the box with dashed lines, which shows the portion of the system most appropriate to compare to a traditional power system.

Table 1. Transmitter Power Levels in different beams

	Trans mitter 1	Transm itter 2	Transm itter 3	Transm itter 4	Total Power
Facility 1	5 kW	5 kW			10 kW
Facility 2	5 kW	5 kW			10 kW
Facility 3			5 kW	5 kW	10 kW
Facility 4			5 kW	5 kW	10 kW
Facility 5	2.5 kW	2.5 kW	2.5 kW	2.5 kW	10 kW

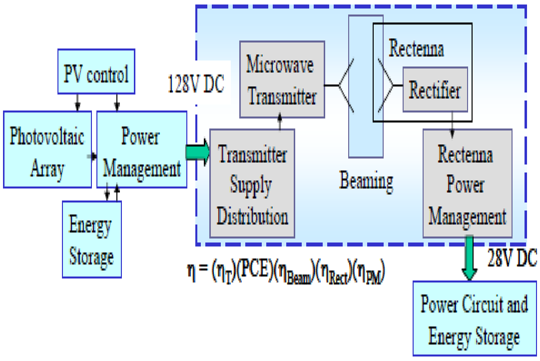

Fig. 3 Overall Architecture
Solar power generation, power management, and grounding on the lunar surface

SINGLE BEAMING CHANNEL ARCHITECTURE

The envisioned lunar WPT system consists of several wireless powering channels, each one depicted in some detail schematically in Figure 4.

The solar power photovoltaic (PV) generation facility is one of the most mature technologiesemployed in the WPT system. A typical photovoltaic system has planar solar arrays for powergeneration and chemical batteries to store excess solar array energy during periods of sunlightand provide power during periods when the load station is in shadow. It is expected that thebatteries will only provide survival power during eclipse.For a future lunar power system, one should consider using a new technology known as aStretched Lens Arrays (SLA).This solar array technology uses a Fresnel lens and high efficiencymulti-junction cells to provide superior PV

A channel consists of an advanced solar arrays, power system based on the International Space Station (ISS) architecture (energy storage, Sequential Shunt Unit (SSU) & Battery Charge/Discharge Units (BCDU), Main Bus Switching Unit (MBSU), Remote Power Distribution Assemblies (RPDAs), Secondary Power Distribution Assemblies (SPDAs)), solar array control, power management and distribution (PMAD), high efficiency RF transmitters, high-directivity transmit antennas, and large-area rectenna arrays with associated DC combining and regulation.

The system architecture also addresses the need for a transmission tower structure, grounding, energy storage, static dissipation, and thermal management.

The blocks shaded in blue in Figure 4are directly related to the wireless power beaming system. Some of the components in the dashed boxes containing the RF transmitters and rectennas would need to be specifically designed for WPT. Some subsystems would likely be the same no matter what power distribution method were to be chosen, including cables.

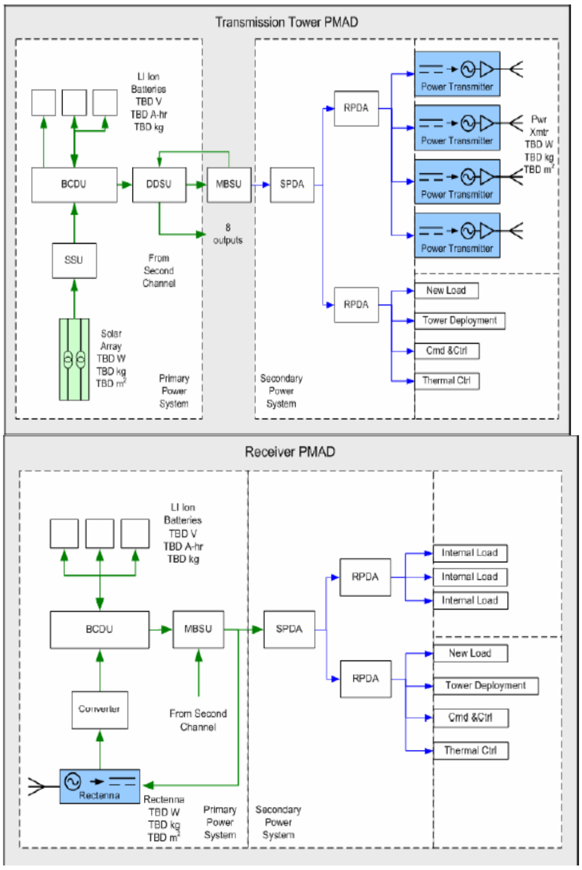

Fig.4 Single beaming Channel Architecture

performance. The Fresnel lens (concentrates the Sun,8 to 1), is light weight, scalable with a capacity of 100's of kW's, provides outstanding radiationresistance, has a built in passive thermal management (radiator), has a high specific power and can operate at high voltages .A single SLA is shown in Figure 5.

Fig 5. Stretched Lens Cell

For a lunar power generation station, Entech, ATK and NASA (Glenn Research Center) have developed a modular 2.5 m X 5 m 4 kW SLA square rigger (SLASR) array as shown in Figure 6. This modular SLASR is highly compactable and is expected to be easily mass produced. Future SLA concepts are expected to have specific power levels in excess of 1000 W/kg.

Fig.6Single Cell Stretched Lens Array enables low mass high efficiency power generation

The power management and distribution (PMAD) system for WPT is very similar to the ISS PMAD System. The main modifications that would be required to a baseline ISS PMAD channel are as follows:

- New concentrator solar arrays will be used instead of conventional planar solar arrays
- New technology Lithium Ion batteries will be used instead of conventional Nickel Hydrogen batteries
- Software modification to support new technology Li Ion batteries and new concentrator Solar Arrays will be required in the form of current and voltage regulation set points and battery charging algorithms.

Grounding can be defined as the electrical connection of the primary reference of the electrical device to a large enough conductive mass such that charges transferred to the mass do not result in a significant increase in the overall charge of the mass. Thus the reference maintains a charge that is stable during the operation of the device. Such a stable reference is useful for reducing electrical noise, and preventing a build-up of charge that could cause arcing to other areas or present a danger to operators or other systems.

WPT channel parameters

The main sub-system for a single wireless powering channel is discussed here, with references to state-of-the art results.

5.2.1. Microwave Transmitter and TransmitterAntenna

The transmitter takes DC input and converts it to a radiated RF output. It consists of a DC-RF conversion oscillator, which is typically low-power and followed by a gain stage and finally a power amplifier (PA).

The size of the antenna is determined by several factors: beaming efficiency for a given range, transmitted power per unit area, ease of fabrication and deployment, etc. The main considerations in the transmitter are power amplifier device technology, efficiency and cost; power amplifier circuit architecture and efficiency; and power combining efficiencies. Power devices for high-power microwave sources can be either tubes, solid-state or solid-state driven traveling wave tubes (TWTs).

For powering applications, linearity and noise are not relevant, and the high efficiency of class E and tolerances to small differences in circuit parasitic parameters give this mode an advantage.

5.2.2. Beaming

the beaming efficiency can be high for line-of-sight links. On the lunar surface, line of sight for a 2-km range requires towers for the transmitters.

5.2.3. Rectification

The transmitted power density is focused on an array of rectennas in the far field of the transmitter. An integrated antenna and rectifier is usually referred to as a rectenna. Rectenna converts microwaves in DC voltage by rectifying microwaves.

5.2.3.1. Rectenna Modules

The rectenna arrays at the load stations will necessarily have large areas .Thediodes in individual rectenna elements can rectify only a limited amount of power and alsoproduce a small voltage, so series/parallel combinations of many elements must inevitably bemade. Distributed power management is designed and integrated at the sub array level to createintegrated power modules that cover a range of power.

Fig. 7 Rectenna Module

The power managementcircuitry achieves two primary functions:
(1) Peak power tracking of the rectenna sub array by matching the input impedance of theconverter cell to the rectenna sub array low frequency output impedance and
(2) Charge control for battery protection and long life charging.The first function of impedance matching is required to achieve high overall system efficiency inthe presence of wide variations in incident power density over the entire receiver aperture. Asingle power converter and management unit is used for both functions to achieve maximumsystem efficiency and to avoid the need to passively dissipate excess energy from the rectennasub array in the case of battery overcharge. As a battery overcharge condition is approached,charge control is achieved by forcing a mismatch between the rectenna output and converterinput impedance, causing the received input power to decrease to match the batteryrequirements. This removes the need for shunt dissipation elements and associated thermaldissipation considerations.A trade-off study needs to be performed to determine the optimal series-parallel configurationand physical layout for each sub-array and the converter topology for maximum systemefficiency.

5.3 System Considerations

Some additional system considerations are summarized here.Astronaut Considerations
• Safety issues for astronauts walking through the beams
• Uncontrolled pointing of the RF transmitter
• Human capabilities analysis and plan
• Antenna side lobe and reflected power safety issues
Transmission Tower
• Deployment in 0.6g
• Testing in 1g
System Design
• Packaging for launch /storage
• Transportation to final location on lunar surface
• Deployment at landing site – Automatic vs. manual
• Assembly Process (Cable management)
• Antenna alignment / point away approach
• Grounding of the various system elements
• Voltage regulation approach
RF WPT Operations
• RF Transmitter / Rectenna Pointing
• Assembly Process
• Maintenance
System Efficiency
• Best common voltage for the system
• Load shedding and management approach
Thermal Control System
• Array and transmitter thermal management
• Electronics thermal management
Other
• Dust mitigation in the presence of large static fields
• Power harvesting of the side lobes
• Energy storage sizing and selected battery technology
• RF and sub-RF EMI mitigation
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CONCLUSION

Lunar Wireless Power Transfer is replaceable source of power generation in future. It will be clean and use existing technology. It will provide abundant power. It will provide continuous power, only interrupted for three hours each year during the lunar eclipse. It will provide reliable power and will be renewable. The moon's environment is perfect for long term dependable operation of solar power arrays, due to its total lack of atmosphere. Only limited amounts of manpower and materials need to be transported from earth. Most everything needed can be made from lunar materials

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