Lunar Surface-Based Solar Power Wireless Transmission Solar Array Location Assessment

By Ghanim Alotaibi

Abstract

Wireless solar power transmission from one location to another on the lunar surface seems to be an optimum option for future outposts on the moon. The system includes a photovoltaic array, wireless power transmission receiver and transmitter, and storage system. John Mankins has proposed a location for the system based on parameters such as land inclination, average temperature, and average illumination. This research project evaluates two locations to install solar arrays for a wireless power transmission system to generate power for a future lunar outpost. The methodology of evaluation and suggestions for future studies are also presented.

Introduction

The south pole of the moon is a good potential location for a future outpost. There are many factors that make the south pole a suitable candidate. Water and other volatiles are available and relatively abundant at the south pole. Figure 1 shows the location of the lunar outpost concept considered in this research.

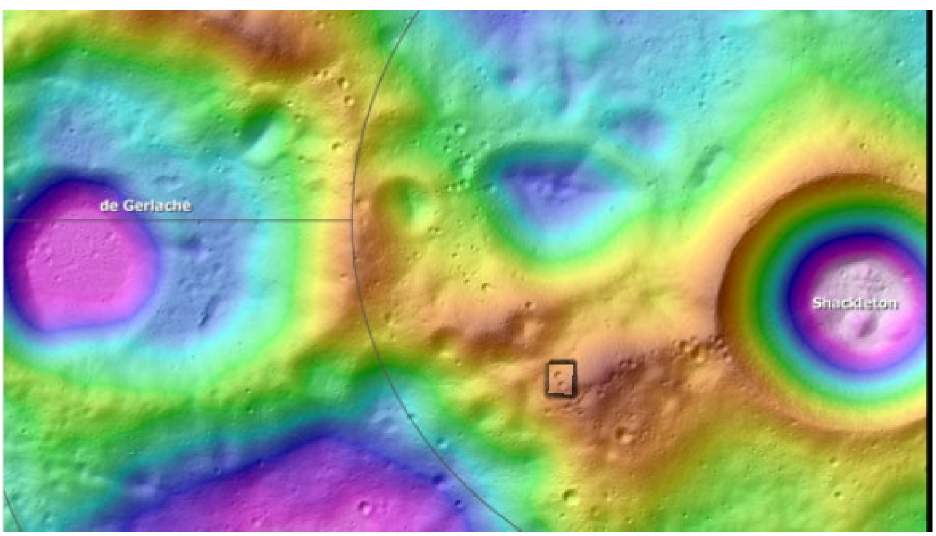

Figure 1: Potential Future Lunar Outpost Location (Inside the Black Rectangle)

Each crater is about 400 m in diameter. The utilization of craters for lunar outposts/settlements may be beneficial as it may offer protection from harmful radiation. This location can support future growth, heat flow, and many other basic requirements for a settlement/outpost to support humans.[1] A detailed discussion of this location is beyond the scope of this paper.

Power is a basic requirement for any lunar outpost concept. Many power generation technologies can be considered for the lunar outpost. Radioisotope thermoelectric generation is high cost and requires complex equipment to be launched from Earth due to the risk of radioactive leaks. Space nuclear reactors can be extremely risky once turned on, and they could contaminate the lunar surface. A solar photovoltaic array installed near the proposed lunar outpost would also be a challenging alternative. The illumination at the outpost positions was measured at 27.8% of the time (including areas at least a few hundred meters away from the outpost). This means a huge photovoltaic array would be required to charge batteries during unilluminated times.

Among the many power generation options, transmitting solar power from a highly illuminated location to the location of the outpost seems the most promising. Illumination time can reach about 100% of the lunar year (depending on the altitude). Also, the atmospheric effects on the moon are negligible, and there is no seasonal variation. Solar power is safe and reliable, as it does not require radioactive materials. High illumination locations are associated with high altitudes and relatively high temperatures. Figure 2 shows this concept of wireless power transmission (WPT).[2]

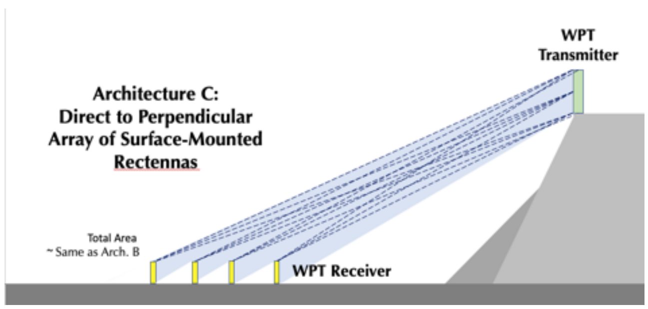

Figure 2: WPT Architecture

As shown, the solar power generator is in a high-altitude location with a high illumination percentage. Power is transmitted to the receiver near the outpost in a location with a low illumination percentage. The following sections discuss the point-to-point power transmission modeling for different locations near the south pole.

Point-to-Point Modeling

Point-to-point modeling is sizing the transmitter, the receiver (rectenna), the storage capacity, and the solar array. This sizing process is based on the solar power requirement

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[1] John Mankins, "Lunar Settlement Case Study," Lecture, COM 501—Energy, Civilization, and Economy Course, Kepler Space Institute, April 2020.

[2] Lunar Planetary Institute, "Lunar South Pole Atlas," April 2020, www.lpi.usra.edu/lunar/lunar-south-pole-atlas/.

(power demand of the outpost) and the environment. The assumptions for the DC-RF and RF-DC transmission efficiency and the efficiency of the solar panels are shown in the appendix.

The actual power requirement for the lunar outpost needs more consideration and further study. For this research, a power requirement of 100 kW is assumed. The sizing of the receiver assumes 85% efficiency in the RF-DC transmission. The sizing also depends on the distance between the receiver and the transmitter, beam frequency, and transmitter diameter. The transmitter sizing is based on 80% DC-RF transmission efficiency, 39% beam interception efficiency, and 96% beam coupling. This gives a receiver diameter of 58 m on the floor. Applying a 60° correction using the cosine law, the diameter becomes 117 m. The minimum transmitter diameter is calculated at 40 m. If the solar photovoltaic panel area is equal to the transmitter area, and has an efficiency of 30%, the power output will surpass the required power of 100 kW given an insolation of 1,398 W/m^2. The average temperature for the receiver and solar power generation system is assumed to be 40K.

This study evaluates the performance of the transmitter in several locations. This means that the illumination, the distance between the receiver and transmitter, the correction angle, and the receiver average temperature will be varied as we change the location.

Location Evaluation

The two most important parameters to favor one location over another are the illumination percentage and the distance between the transmitter and the receiver. Higher illumination means more power output for the same solar array area and a smaller storage system. A shorter distance between the receiver and the transmitter means a smaller transmitter area, and therefore a lower cost. Another important parameter that should be considered is the location's accessibility from the outpost.

The two locations on this research are shown in Figure 3. Both locations were selected since the maximum and average temperature of the location is higher than other locations near the outpost. This indicates a higher illumination because the sun is the only source of heat on the lunar surface.

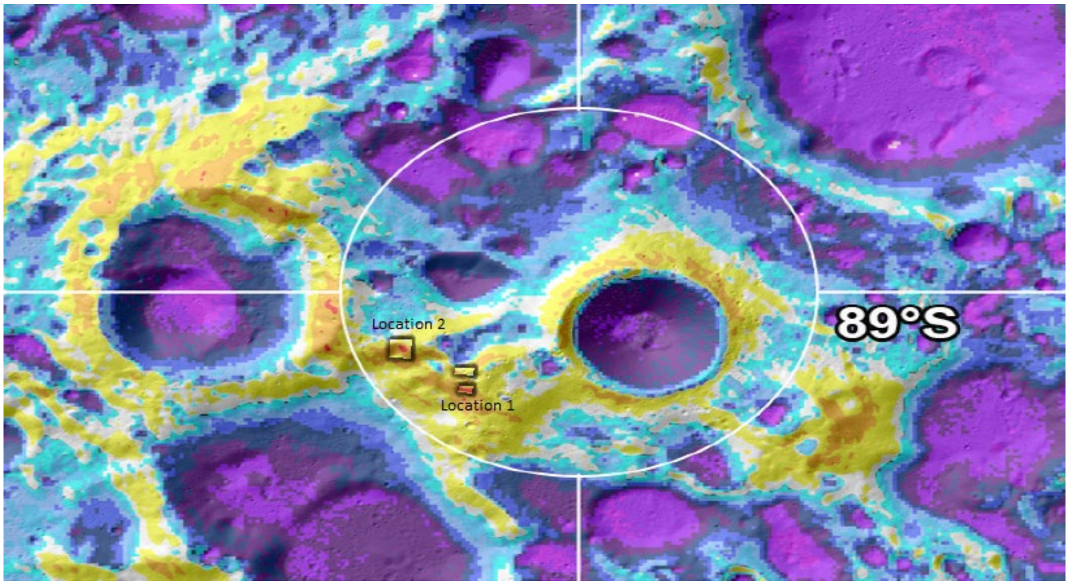

Figure 3: Locations of Transmitter Tests.
Location 1 is south of the outpost location, while Location 2 is northwest.

The illumination percentage was calculated based on data from the Lunar Planetary Institute.[3] The data is basically a one-month movie of polar illumination for the south pole from the NASA Clementine Mission. The two locations of interest were identified in the movie, and as the movie was playing, the illumination time was measured on each location using a stopwatch. The movie was originally two seconds long and it only covered the source. Movie editing software was used to slow down the two seconds, and the total duration of the movie was extended to four minutes and nine seconds.

A transparent sheet was used to draw the borders of the permanently shaded areas. The transparent sheet was placed on the screen, and the movie was played. The permanently shaded regions in the Shackleton Crater and the de Gerlache Crater were perfectly identifiable as almost full circles. Using other maps to identify the distances to the locations of interest, every centimeter in the movie map was found to be equivalent to about 15.5 km. Therefore, it was possible to identify the desired locations on the transparent sheet. As the movie was projected onto the background of the transparent sheet, the illumination time was measured at the desired location.

Results and Discussion

Location 1

As mentioned above, Location 1 was selected because its surface temperature is higher than other locations. This indicates higher illumination. Also, Location 1 is very near the outpost location. It is 3.3 km south of the outpost. The shorter distance means a smaller transmitter size and easier access. The topography and slopes maps are too low

[3] Lunar Planetary Institute, "Lunar South Pole Atlas."

in resolution for a more extended discussion about accessibility. Location 1 was illuminated for 48% of the time. Table 1 summarizes the findings for Location 1:

Table 1: Measurements for Location 1

Parameter	Measurement
Illumination percentage time	48%
Distance to outpost	3.3 km south
Average temperature	190K
Correction angle	30°

The correction angle is related to the difference in height between the desired location and the outpost. The low resolution of elevation in topographical maps makes it very challenging to calculate an accurate number. However, it seems that the two locations are not very different in elevation, but Location 1 is slightly higher. For this reason, an angle of 30° was assumed.

Using the measurements for Location 1 and based on the assumptions and data presented above about the point-to-point model, the sizing for the receiver, transmitter, and storage system are shown in Table 2:

Table 2: WPT Sizing Results for Location 1

Parameter	Size
Transmitter diameter	40 m
Receiver diameter (at angle on the floor)	8 m (9 m)
Time of storage	52% of the time (368 hours/month)
Storage required at transmitter	146,613.5 kWh
Storage required at receiver	36,816 kWh

The scale for the illumination map movie was 1 cm for each 15.5 km. The dots on the transparent sheet can represent 100 meters or more. Therefore, making accurate measurements of illumination is challenging given the available data. For Location 1, illumination was present very near the dot at the start of the movie. This means that illumination was present a few hundred meters away from the identified location. To identify the illumination location better, it is important to measure the illumination of sites near Location 1.

The WPT system sizing numbers above look promising, except for the storage system. It is therefore important to place multiple WPT systems in various locations with alternating illumination cycles to reduce the storage requirements. Sizes of 40 meters for the transmitter and 9 meters for the receiver are easily achievable.

Location 2

Location 2 is 9.2 km away from the outpost. Location 2 was easier to evaluate as the location is clearly on top of a small crater edge, which is higher than the surrounding area. In the illumination movie, the illumination pattern identifies the location. Table 3 shows the measurements for Location 2:

Table 3: Measurements for Location 2

Parameter	Measurement
Illumination percentage time	47%
Distance to outpost	9.2 km south
Average temperature	190K
Correction angle	50°

The correction angle was assumed to be larger because Location 2 is clearly higher in elevation than Location 1 and the outpost location. However, the illumination time is almost the same as for Location 1. Table 4 shows the point-to-point model run for Location 2:

Table 1: WPT Sizing Results for Location 2

Parameter	Size
Transmitter diameter	40 m
Receiver diameter (at angle on the floor)	21 m (33 m)
Time of storage	53% of the time (375 hours/month)
Storage required at transmitter	149,433 kWh
Storage required at receiver	37,524 kWh

The transmitter diameter is the same as for Location 1 because the assumption was that the transmitter size equals the solar array size. The longer the distance between transmitter and the receiver, the larger the necessary receiver diameter.

Clearly, Location 1 seems better due to smaller receiver size, slightly lower storage requirement, and easier accessibility. However, uncertainties due to the low resolution of the maps makes it difficult to decide. The illumination cycle starts at different times at the two locations, which means that installing two systems at both locations will definitely reduce the storage requirement.

Future Studies

Further studies will be needed to optimize the location of a WPT system. It might be a good idea to create software that will measure illumination and temperature at every location on a given map of the lunar south pole. Combing this software with high-resolution data will allow easy evaluation of many locations using the above methodology. Depending on the available data, a first version of such software can be created to replace the manual methodology used in this research. With more accurate data, the software can be enhanced later.

An optimized solution may involve the installation of several WPT systems with differing illumination periods. A trade-off study will be required for accurate assessment given the parameters of the WPT components, sizes and masses, and storage requirements. Therefore, software that assesses illumination with high-resolution data would be a good investment for a significant cost reduction in power generation for a future lunar outpost.

Conclusion

WPT generated by solar photovoltaic arrays is the most suitable available technology for a future lunar outpost at the south pole of the moon. This research evaluated two different locations at the moon's south pole to install photovoltaic solar arrays for a WPT system. The available data resolution was low; however, the manual methodology presented above may offer a good start for future research projects.

Location 1 is slightly more suitable for the installation of the solar array. The shorter distance reduces the size of the receiver compared with Location 2. An optimum solution can be achieved by installing several systems with differing illumination periods. This will significantly reduce the storage requirement. This means that the evaluation of many locations is required. However, using a manual methodology with low-resolution data is a major challenge. Therefore, software that can automate the methodology for research may reduce the cost of power generation for future outposts significantly.

Appendix

Lunar Polar Power Distribution — April 23, 2020

Case 1 - Power to Receiver on "Floor" @ 2.45 GHz

SSP System - in PEL		
External Environment		
Duration of each Lunar Day	708	hrs
% time SSP Array in the Sun	47.0%	percentage
Hours SSP Array in Sun	332.76	hrs
Average Temperature (PEL)	190	°K
Average Temperature (PSR)	40	°K
Insolation (When Lit)	1,368	W/m^2
WPT		
SPG Power Output Required	398,233	W
Insolation (when Lit)	1,368	W/m^2
Transmitter Area	1,256.6	m^2
PV Area	1,256.6	m^2
Average Power per Area	316.90	W/m^2
PV Efficiency	30.0%	Percentage
Max Possible SPG Power @ 1-to-1	516	kW
Max Possible SPG Power @ 2-to-1	1,031.4	kW
Energy Storage Option		
Time of Storage	375.24	hrs
Storage at Transmitter		
Energy Storage Required	149,433.0	kWh
Storage at Receiver		
Energy Storage Required	37,524.0	kWh
Receiver Cosine Correction		
	0.6428	
Angle	50	Degrees
If "Distance" is at 2-times Elevation		

WPT DESIGN BASELINE PARAMETERS					
Speed of Light	299,792,458	m/s			
Frequency	2,450,000,000	Hz			
Wavelength	0.122364269	meters	Power transmission RF wavelength		
Transmission Distance	9	km (Xmttr-Rcvr)	Distance from Xmttr to Rcvr		
Diameter (Xmttr)	40	meters	Diameter of the transmitter		
"Tau"	2.44	Parameter	**Parameter for 96% Beam Coupling**		
Transmission Eff	99%	Percentage	Percentage Transmission (inc. Atm Losses)		
Max Beam	96%	Beam Coupling	Max Beam Coupling Efficiency		
Required Beam	39%	Beam Intercepte	Desired Beam Interception Efficiency		
XMTTR SIZING CALCULATIONS					
Xmttr DC Input	398,233	Watts			
Xmttr DC-RF Eff.	80.00%	Percentage			
Xmttr RF Output	318,586	Watts			
SIZING OF RCVR					
RF-DC Efficiency	85%	RF-to-DC	Percentage of RF converted to DC at Rectenn		
	Diameter (Possible Receiving Circle) = 2.44 * Wavelength * Distance (Xmttr-Rcver)/Diam				
D (Circle)	21	meters	Area R	361.7	m^2
D (On "Floor" @ Angle)	33	meters	Area R	875.4	m^2
RF Power @ Rcvr	117,647	Watts	RF Power incident on the Circle		
DC Power Required @ Rcvr	100,000	watts	Potential DC Power Output		
PEAK POWER @ RCVR					
Peak WPT Power at Receiver	116.66	Watts/m2			
AVERAGE POWER @ RCVR					
Average Power	40.83	Watts/m2	Very Rough Estimate…!		
EDGE POWER @ RCVR					
Min Power	8.17	Watts/m2	Very Rough Estimate…!		
	0.82	mW/cm2			
PEAK POWER = Power (Transmitter) * Area (Transmitter) / (Wavelenth * Wavelength * Distance (Xmttr-Rcver)					

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About the Author: Ghanim Alotaibi is a mechanical engineer who works in the Physics department at Kuwait University. He is working on the first space mission in Kuwait and is considered the first person in Kuwait to hold a full-time space-related job. Ghanim is also the project manager for the "Moon Village—Participation of Emerging Space Countries" project. The project's aim is to involve developing countries in moon activities to make moon exploration more diverse.

Ghanim worked for the Kuwait Oil Company for six years before he obtained his master's degree from Freiburg University, Germany in solar energy. Since he was an undergraduate student, he has been involved in many space activities. He was the Middle East Regional Coordinator for the Space Generation Advisory Council and he performed two field rotations as an analogue astronaut at the Mars Desert Research Station. Ghanim is also an amateur astronomer with an interest in the photometry of variable stars and he is a graduate of the International Space University.

Editors' Notes: Ghanim Alotaibi is a scholar at KSI, where he has built on the work of Professor John Mankins, the globally renowned expert in Space Solar Power. In keeping with Mankins's thoroughly researched and concrete recommendations, Alotaibi here considers arrangements for solar power on the moon and makes recommendations for a wireless power transmission system. This solution is specifically designed for a small settlement at the South Pole of the Moon near Shackleton Crater, in keeping with plans developed for the *Moon Village Association*. Such a solution may very well be implemented in just a few short years as multiple international organizations plan for a return to the Moon. ***Gordon Arthur and Mark Wagner.***