DECEMBER 2017 M.Sc. Thesis in Mechanical Engineering ESRA DEĞİRMENCİ

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PERFORMANCE ESTIMATION OF LUNAR SOLAR POWER SYSTEMS FOR THREE LOCATIONS ON TURKEY

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Performance Estimation of Lunar Solar Power Systems for Three Locations on Turkey

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Supervisor

Prof. Dr. Mehmet Yasar GUNDOGDU

by

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Esra DEĞİRMENCİ

ABSTRACT

PERFORMANCE ESTIMATON OF LUNAR SOLAR POWER SYSTEMS FOR THREE LOCATIONS ON TURKEY

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M.Sc. in Mechanical Engineering

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The general purpose of this study is to do a detailed research and design a computer program on lunar solar power systems which makes possible to generate solar energy during 24 / 7 continuously via excessively different and upper technology than the consuetudinary methods with restricted conditions and limited sources on Earth.

In this study, the needed technology of lunar solar power systems is examined, construction steps are discussed and a computational model is designed with Matlab Gui 2011. It is aimed with this model that getting 20 TWe energy on Earth and doing antenna calculations under different conditions and with different possible technologies to decide the best options for a LSP system. The site analysis are done for three city in Turkey as Ankara, Konya and Gaziantep to construct receiver center for microwave power transmission. Konya might be the best option because of the latitude effect and annual rainfall rate with 5020,31 MW net power value for 2,45 GHz^{-1} and 230 W/m^2.

With respect to the theoretical and computational results; it is concluded that the Lunar Solar Power System can be a safe and clean alternative to current options to meet Earth's total energy need for long decades in case of economic and technical problems are solved.

Key Words: Lunaring, Lunar Solar Power, Energy, Microwave, Laser, Modeling

ÖZET

LUNAR GÜNEŞ ENERJİ SİSTEMLERİNİN TÜRKİYE'DEKİ ÜÇ LOKASYON İÇİN PERFORMANS TAHMİNLEMESİ

DEĞİRMENCİ, Esra

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Tez Yöneticisi: Prof. Dr. Mehmet Yaşar GÜNDOĞDU

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Bu tez çalışmasının genel amacı, dünya üzerindeki kısıtlı ve sonlu kaynakların aksine, tamamen farklı ve üst düzey bir teknoloji ile 7/24 kesintisiz güneş enerji üretimini mümkün kılan lunar güneş enerji sistemleri üzerine kapsamlı bir araştırma yapmak ve bir bilgisayar modellemesi geliştirmektir.

Bu çalışmada, lunar güneş enerji sistemleri için gerekli olan teknoloji incelenmiş, kurulum aşamaları tartışılmış ve MatlabGui 2011 ile bir LSP modellemesi yapılmıştır. Bu modelleme ile farklı koşullar altında, olası teknolojileri kıyaslayarak Dünya'da 20 TWe enerji elde edebilmek ve anten hesaplamaları yapabilmek amaçlanmıştır. Mikrodalga alıcı merkezinin kurulumu için Türkiye'de Ankara, Konya ve Gaziantep olmak üzere 3 şehir incelenmiştir. Enlem etkisi ve yıllık yağış miktarı göz önünde bulundurulduğunda, 2,45 GHz^{-1} ve 230 W/m^2 icin Konya'nın 5020,31 MW net enerji değeri ile en iyi seçenek olabileceği öngörülmüştür.Teorik ve kompütasyonel sonuçlar çerçevesinde, şayet ekonomik ve teknik sorunlar yenilirse, lunar güneş enerji sistemlerinin uzun yıllar boyunca dünya enerji ihtiyacını karşılamak için mevcut seçeneklere temiz ve güvenli bir alternatif olabileceği sonucuna varılmıştır.

Anahtar Kelimeler: Ay, Aydan Güneş Enerjisi, Enerji, Mikrodalga, Lazer, Modelleme

To my family and best friends

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ABBREVIATIONS

LSP	Lunar Solar Power
SPS	Space Power Satellite
NASA	National Aeronautics and Space Administration
DOE	Department of Energy (USA)
GEO	Geosynchronous Earth Orbit
LEO	Low Earth Orbit
JAXA	Japan Aerospace Exploration Agency
ISAAC	The International Society for Augmentative and Alternative Communication
SCR	Silicon Controlled Rectifier
GCR	Galactic Cosmic Radiation
PV	Photovoltaics
CPV	Concentrator Photovoltaics
Si	Silicon
GaAs	Gallium Arsenide
CIGS	Copper Indium Gallium Selenide
IEEE	The Institute of Electrical and Electronics Engineer
ICNRP	The International Commission on Non- Ionizing Radiation Protection
RF	Radio Frequency

DC	Direct Current
AC	Alternating Current
EM	Electromagnetic Radiation
YAG	Yttrium Aluminum Garnet
LPTS	Laser Power Transmission System
MPT	Microwave Power Transmission
ITU	The International Telecommunication Union

CHAPTER 1

INTRODUCTION

Energy is at the core of economics and social life in today's world. Nowadays, we totally depend on an abundant and continuous supply of energy for living and working in high standards. As a consequence of this, energy growth is directly linked to well-being and prosperity across the globe. It is an indisputable truth that meeting this growing demand for energy safely and environmentally is a key challenge, especially after the growing concerns about global warming and seasonal change due to greenhouse gases. Differently from the all renewable and non-polluting sources, solar energy is the basic source of commercial power because the sun is a sustainable source of energy for us. Nevertheless, current renewable energy sources with using current techniques are evaluated as that they will not provide the future energy demand [1] because of the rapid increase of population. According to the statistical and academic researches, by the year 2050, people will require at least 20,000 GWe of power [2] that is more that 10 times the 1,800GWe now provided by the world's electric power stations [23]. The situation is comparatively critical for Turkey, with a rapidly increasing population and with a growing economy, it has become one of the fastest growing energy markets in the world in the last decades [12]. On the other hand, like any other developed and also developing countries, Turkey gives big importance to the renewable energy sources, especially to the solar energy, considering the self sufficiency about energy and environmental pollution. But unfortunately, domestic energy source limits of Turkey in light of its growing energy demand have resulted in dependency on energy imports [11]. It does not matter with a local or global point of view, conventional energy systems become useless for us in the near future. At this point, we have to think about new ideas to get limitless power for the next generations. The answer can be the Moon.

The equator of the Moon approximately receives 13,000 TWs of solar power [10] and building a commercial power system to transfer the solar energy on Moon to the Earth at a moderate price can be a solution. In 2013, The Shimizu Corporation, a Japanese construction firm has introduced the biggest solar power concept ever. It starts with constructing a huge lunar base and a belt of solar cells around the Moon's 11,000-kilometer equator, then continues with transforming the electricity into microwaves or lasers to beam to Earth, and finishes on ground with transforming the beams back to electricity as a commercial power. This concept is named shortly as Luna Ring and according to the mathematical calculations of the company, Luna Ring can supply World's total energy need for long decades [4]. The biggest advantages of the Lunar solar power systems are that it could generate 24 / 7 continuous clean energy and it is not affected from the seasonal changes and day-night cycle unlike solar systems on Earth. Developing such a system on moon can be more efficient than limited terrestrial applications on Earth because of the period of night time darkness. Solar power at any point on the surface of Earth is unpredictably irregular and captive to changes in regional and global climate [10] but a lunar based system in continuous sunlight doubles the total power generated on Earth in the same 24 hour period.

The main purpose of this study is to design a computational model for lunar solar power systems to supply 20 TWe power to Earth with different transmission types, different solar cells, different concentration rates on Moon and different weather conditions on Earth to compare the efficiencies of the possible technologies under the different conditions. Calculating the final energy on Moon, number of solar cells, covered area and width of the lunar belt computationally gains us time to decide best options for a LSP system. Also, observing graphically the effects of frequency selection, site selection, weather condition which causes atmospheric attenuation and the beam intensity at the center of the antenna can help us while constructing a receiver center in Turkey.

In the next chapter of this study, a literature survey is done under the tittle of Historical Background of Lunar Solar Power Systems. Starting from the origin of the lunar solar power idea comes from the concept of Peter Glaser in 1968 and up to the idea of Japanese company, Shimizu in 2013, all the space solar power concepts are introduced. The needed technology of lunar solar power systems and physical construction steps are examined to produce the energy from solar cells on Moon and transfer it to Earth via microwave and laser transmission. The basics of a lunar solar power system are concentrated as; lunar base, solar cell technology, wireless power transmission technology and transmitter–receiver antenna facilities. Also, thermodynamical calculations and efficiency analysis of previous studies are examined in this chapter.

In fourth chapter, a mathematical and computational model is designed to get 20 TWe of energy on Earth to meet the energy demand of the world by the year 2050, in a safe and environmental manner. The macro parameters of a lunar solar power system and equivalent efficiency values are listed. The final power on Moon, number of cells along the lunar equator, the diameter of receiver antenna and the net power on this antenna are decided due to this model.

In the conclusion and evaluation part of this study, all subjects and data derived from the studies with computer program related with lunar based solar system efficiency are summarized. Economic viability of lunar solar power systems are considered together with a political and legal perspective. Also, in order to enable lunar based solar systems as a commercial value, actions to be taken and solution proposals are discussed.

CHAPTER 2

LITERATURE SURVEY

2.1 HISTORICAL BACKGROUND OF LUNAR SOLAR ENERGY SYSTEMS

Lunar Solar Power System concept comes from the idea of space based solar power systems and first time P. Glaser [5,14] introduced the solar power satellite (SPS) concept to obtain continuous solar power independently from atmospheric effects as shown in Figure 2.1. After his invention NASA and DOE created 30 M$ fund to analyze technical and economic feasibility of solar satellites between the years 1977–1981 [6,7]. During 1995-1997, NASA lead off a special study names as ‘fresh look’ to determine the capability of SPS [8] to get commercial power as an alternative to current market options.

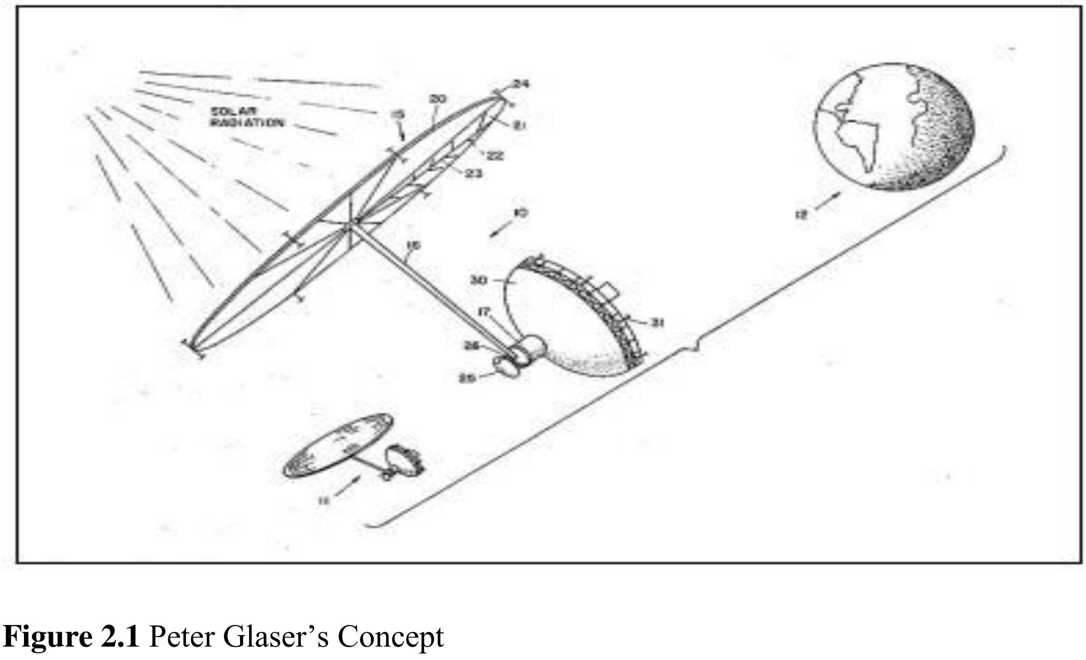


Figure 2.1 Peter Glaser’s Concept

Several concepts are represented under this study and one of them is Sun Tower which is a gradient stabilized system that solar concentrators and magnetron segments are used.

Other one is the Solar Disk which uses differentially spinning elements that installed in GEO. This model is rotationally stabilized and spirally constructed [17]. Then SPS- ALPHA model is introduced by Mankins. SPS-ALPHA is also a GEO-based system. Thin-film mirrors and coherent microwave beams are preferred in this concept [15]. Meanwhile, JAXA perhaps shows the greatest interest on space solar power systems and has a LEO –based plans of wireless power beaming by 2015 [18]. All design summaries of these systems are listed in Table 2.1. Unfortunately, all these concepts are very expensive and all have some disadvantages [21]. As an alternative to SPS concepts, Criswell offers his lunar solar power idea in 1980. In his concept, LSP System uses bases on opposite faces of the Moon to take the sunlight continuously and each base sends microwave power beams to the receivers on Earth when the receiver antennas can see the Moon. The basic system design is shown in Figure 2.2.

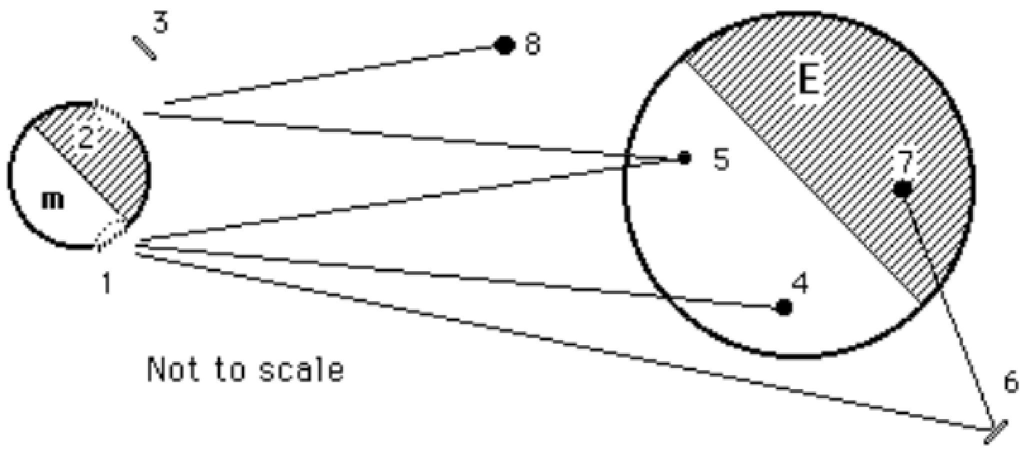


Figure 2.2 Criswell’s Lunar Solar Power

It consists of the power bases that are numbered as 1 & 2, to receive sunlight during a lunar month. Depends on the day – night cycle on Moon, collected power can beam to Earth from one of the active basis. Orbital mirrors are showed as 3 & 6 to redirect the beams, and receiver antennas or with another word, rectennas on Earth numbered as 4, 5 & 7 can get the power during 8 hours in a day while they can view the Moon. Low intensity microwave beams can be directed from each base to receivers on Earth 4 & 5 and in space 8 that convert the microwaves back to electrical power. Earth-orbiting satellites make possible to redirect beams to receivers located anywhere on Earth while they cannot view the Moon [24]. The preferred beam intensity is around

230 W/m^2 recommended for commercial power transmission [23]. Also, Criswell claims that the diameter of the receiver and transmitter antennas can be sized from 200 m to 1,000 m to permit the usage of earth-orbiting redirectors. The location of the bases on Moon and rectenna centers on Earth can be as in Figure 2.3. Active and inactive bases-rectennas changes due to the Moon – Earth rotation. Antenna sizing criteria will be explained and related calculations will be done in Chapter 3. For a 0.266 % overall efficiency and to produce 20,000GWe, one would need to cover 15,3 % of the lunar surface [25] and on Earth receiver areas total to ~10•10^4 km^2 and individual rectennas can be as small as ~0.5 km in diameter and output ~40 MWe. One can conclude that increasing the diameter of the receiver antenna increases the amount of output power.

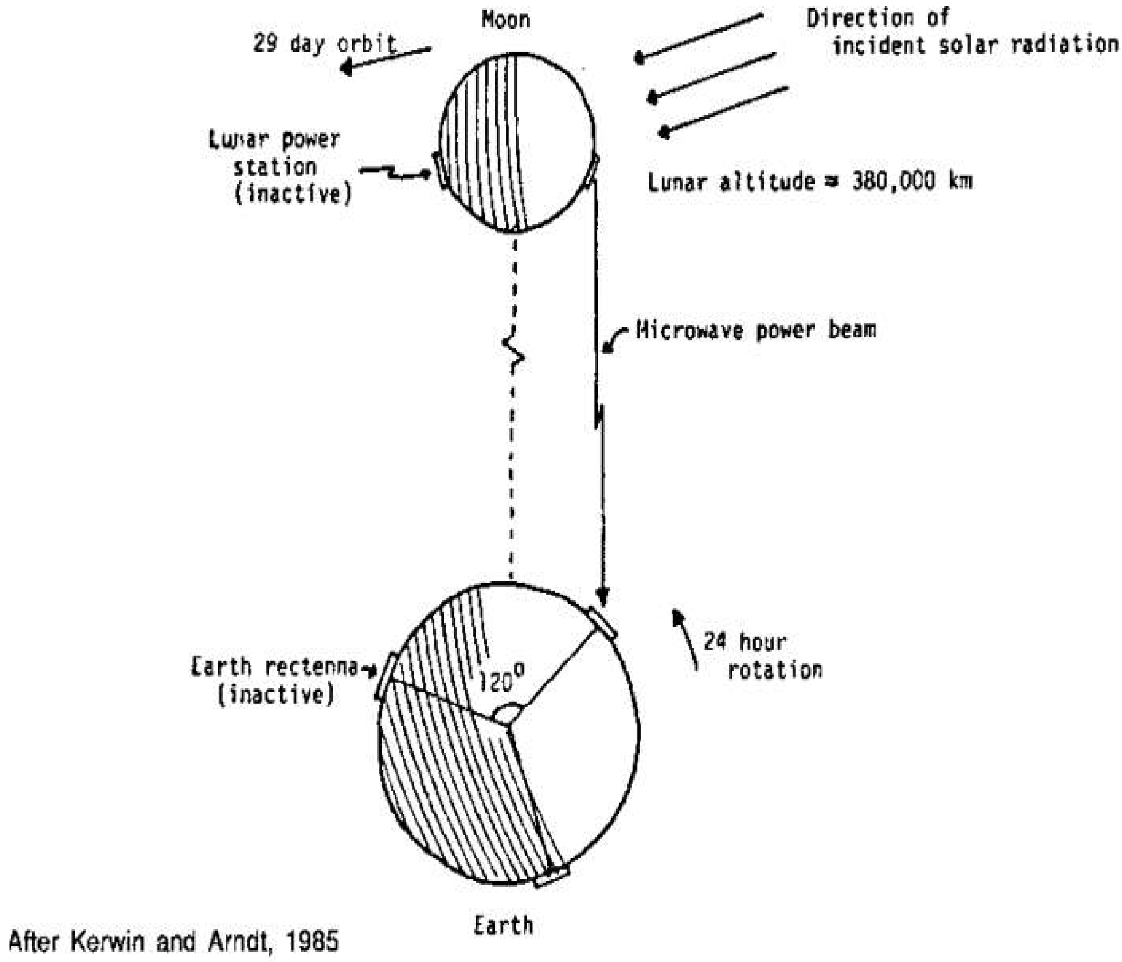


Figure 2.3 Effects of Earth- Moon Motion and Locations of Bases

In 2013, The Shimizu Corporation, pronounced their huge idea. They plans to start to project up to 2035 and employ a remotely controlled robotic army to take on tasks like excavating, ground leveling and installing solar panels on prepared platform. According to the design of the system, transmission facilities on Moon both for microwave and laser will be installed on the near side of the Moon which is always faces to Earth similar to Criswell’s model. Unfortunatelly, this idea has brought with lots of questions. Because, it is a gigantic concept that needs for integration of machinery transportation from Earth and communication between tele-operated robots to manage the actual construction on the Moon's surface.

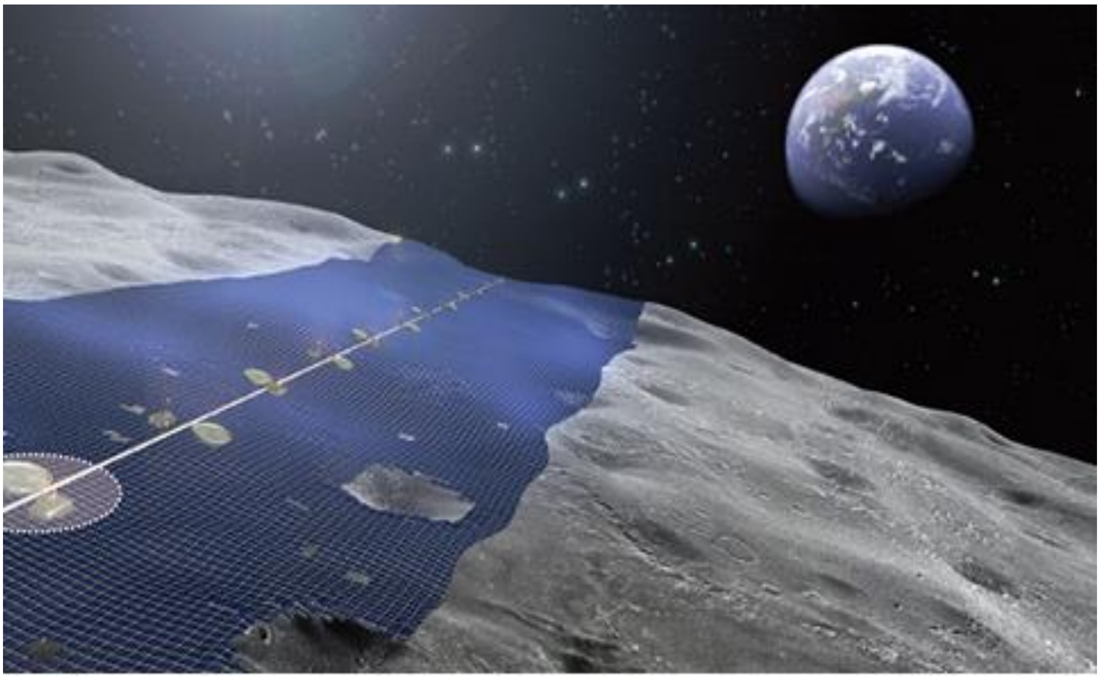


Figure 2.4 Shimizu’s Solar Cell Design

On the other hand, when one compares the SPS and LSP systems, the biggest advantage of the LSP system is, it reduces the operational mass launched from Earth per kW-hour delivered to terrestrial energy markets on Earth. However, the LSP requires initial installation of large-scale infrastructure on the Moon prior to the beginning of power system construction but it eliminates the need for large scale ISAAC platforms in LEO or GEO.

Table 2.1 Summary of Space Based Solar Power Designs

Design	Institution	Orbit	Structure	Capacity	Energy Production	DC-RF	(f/λ)	D_t	D_r
NASA DOE 1979	NASA DOE	GEO	5x10x0.5 km Monolithic	5 GW	Single Crystal Si/GaAlAs	Klystron	2.45 GHz	1 km	10 x 13 km
Sun Tower 1997	NASA (Fresh Look)	LEO-MEO GEO-SSO	15 km Backbone Modular	100-400 MW	Multi-Junction Solar Cell	Magnetron	5.8 GHz	260 m	4 km
SolarDisc 1997	NASA (Fresh Look)	GEO	3-6 km in diameter Modular	2-6 GW	Thin Film (CIS) Solar Cell	Magnetron (%71)	5.8 GHz	1 km	5.6 km
ISC 2000	NASA (SERT)	GEO	Modular Concentrati ng Mirror Integrated	1.2 GW	Multi-Junction Solar Cell	E Class GaN	5.8 GHz	500 m	7.4 km
JAXA 2003	JAXA	GEO	Modular Concentrati ng Mirror Sand Modul	1 GW	Multi-Junction Solar Cell	Magnetron	5.8 GHz	1 km	3.4 km
Lazer 2004	JAXA	GEO	Modular	1 GW	Solar-pumped Solid-State Laser Nd:YAG	-	1.06 μm	-	-
JAXA 2004	JAXA	GEO	Modular Symmetric Reflective Mirror	1 GW	Multi-Junction Solar Cell	Magnetron	5.8 GHz	1.8 km	2.45 km
Sail Tower 2002	ESA/DLR	GEO	15 km long Backbone Modular	275 MW	Thin Film ($CuInSe_2$) Solar Cell	Magnetron	2.45 GHz	1 km	11 x 14 km
"Tethere d 2005	USEF	GEO	Modular Connected to Main Modular	1.2 GW	Thin Film Solar Cell	Magnetron	5.8 GHz	3.8 km^2	4 km
SPS-ALPHA 2012	NASA (NIAC)	GEO	Modular	1 GW	Multi-Junction Solar Cell	Semicondu ctor Amp.	5.8 GHz	1.3 km	-

There are several reasons to prefer LSP system instead of SPS or terrestrial applications in technical aspects and they can be listed as below;

- First of all, the Moon has ideal environment to install large area solar panels.
- Lunar surface's solar flux amount is foreseeable.
- Because of the lack of air and water on Moon, large solar cells and other electronic devices will be more durable.
- Robust solar collectors can be produced with current technologies that they can be designed as unaffected by years of exposure to solar cosmic rays and the solar wind on Moon.

- Sensitive circuitry of the system and also the wiring can be hidden under lunar soil to be protected from solar radiations and high temperature differences. Also, all the components of the LSP system can be made from lunar soil and in this way, cost of the system may be reduced effectively.
- The high cost of transportation is cancelled by sending machines that produce system components and supplies power to different parts of the world.

2.2 THE TECHNOLOGY OF LUNAR SOLAR POWER SYSTEMS AND PHYSICAL CONSTRUCTION

2.2.1 THE LUNAR BASE

There are too many factors that affects the design of a lunar base, but two of them are very important and will be discussed here. First one is cosmic radiation on moon. Previously prepared reports about radiation levels at the lunar surface say that approximately 1.5 m of regolith must be used to prepare a shielding to be secure from high density radiation. With this thickness of shielding, regolith on supporting structures can block the radiation and it can be a viable concept for the base [9]. The main reasons of the difference between Earth and Moon radiations at the surface are that Moon does not have a strong magnetic field and a thick atmosphere, unlike Earth [32].

Three major radiation types in the lunar environment are shown in the Table 2.2. Because of the ionization energy loss of the SCR, they react with the lunar surface's top few centimeter, but these events occur irregularly [33,34]. These events causes potentially the biggest hazard. On the other hand, it is difficult to estimate their intensity and occurrence. The GCR are the most penetrating radiation type but prediction of their occurrence is possible, unlike SCR [35]. Secondly, maximum use of lunar materials for the construction is very important but there are too many differences between Earth and Moon and while designing a lunar base all these differences must be consider. The properties of Moon and Earth can be listed as in Table 2.3**.**

Table 2.2 Radiation Types in the Lunar Environment

Type	Solar Wind	Solar Cosmic Rays	Galactic Cosmic Rays
Nuclei energies	~0.3–3 keV/u*	~1 to >100 MeV/u	~0.1 to >10 GeV/u
Electron energies	~1–100 eV	<0.1 to 1 MeV	~0.1 to >10 GeV/u
Fluxes (protons/cm²sec)	~3 × 10⁸	~0–10⁶†	2–4
Particle ratios†			
electron/proton	~1	~1	~0.02
proton/alpha	~22	~60	~7
L ($3 \leq Z \leq 5$)/alpha	n.d.	<0.0001	~0.015
M ($6 \leq Z \leq 9$)/alpha	~0.03	~0.03	~0.06
LH ($10 \leq Z \leq 14$)/alpha	~0.005	~0.009	~0.014
MH ($15 \leq Z \leq 19$)/alpha	~0.0005	~0.0006	~0.002
VH ($20 \leq Z \leq 29$)/alpha	~0.0012	~0.0014	~0.004
VVH ($30 \leq Z$)/alpha	n.d.	n.d.	~3 × 10^{-6}
Lunar Penetration Depths			
protons and alphas	<micrometers	centimeters	meters
heavier nuclei	<micrometers	millimeters	centimeters

It can be seen that, the temperature difference between the lunar day and night is extremely high if it compares with Earth. Also, while building a lunar base, the extension potential of system must be considered. The living areas, laboratories, and industry areas on Moon should be self-contained and prefabricated Also, they should have the greatest extent possible. Previously done engineering studies, layout a realistic scenario for power, modeling transportation, surface operations and other requirements [36]. Several innovative architectural designs are introduced using local sources to get the most comfortable lunar habitation.

Table 2.3 Moon vs Earth Property Comparison

Property	Moon	Earth
Mass	7.353×10^{22} kg	5.976×10^{24} kg
Radius (spherical)	1738 km	6371 km
Surface area	37.9×10^6 km²	510.1×10^6 km² (land = 149.8×10^6 km²)
Flattening*	0.0005	0.0034
Mean density	3.34 g/cm³	5.517 g/cm³
Gravity at equator	1.62 m/sec²	9.81 m/sec²
Escape velocity at equator	2.38 km/sec	11.2 km/sec
Sidereal rotation time	27.322 days	23.9345 hr
Inclination of equator/orbit	6°41'	23°28'
Mean surface temperature	107°C day; -153°C night	22°C
Temperature extremes	-233°C(?) to 123°C (Table 3.3)	-89°C to 58°C
Atmosphere	~10⁴ molecules/cm³ day 2×10^5 molecules/cm³night	2.5×10^{19} molecules/cm³ (STP)
Moment of inertia (1/MR²)	0.395	0.3315
Heat flow (average)	~29 mW/m²	63 mW/m²
Seismic energy	2×10^{10} (or 10¹⁴?) J/yr†	10^{17}-10^{18}J/yr
Magnetic field	0 (small paleofield)	24-56 A/m

Many studies are done by JAXA and NASA to develop a lunar architectural style and it is concluded that using reinforced concrete has many advantages while constructing a lunar base. The major elements of the lunar soil and their percentages are listed in Table 2.4. As seen from the table most of the components of the concrete can be produced simply from lunar materials [40].

Table 2.4 Major Elements of the Lunar Soil

	Major Elements, wt %				
Element	Mare Soil (10002)	Highland Soil (67700)	Basalt Rock (60335)	Anorthosite Rock (60015)	Glass (60095)
SiO_2	42.16	44.77	46.00	44.00	44.87
Al_2O_3	13.60	28.48	24.90	36.00	25.48
CaO	11.94	16.87	14.30	19.00	14.52
FeO	15.34	4.17	4.70	0.35	5.75
MgO	7.76	4.92	8.10	0.30	8.11
TiO_2	7.75	0.44	0.61	0.02	0.51
Cr_2O_3	0.30	0.00	0.13	0.01	0.14
MnO	0.20	0.06	0.07	0.01	0.07
Na_2O	0.47	0.52	0.57	0.04	0.28

The shape of concrete module decided as hexagonal column by Shimizu as shown in Figure 2.5. which allows multi-directional extension.

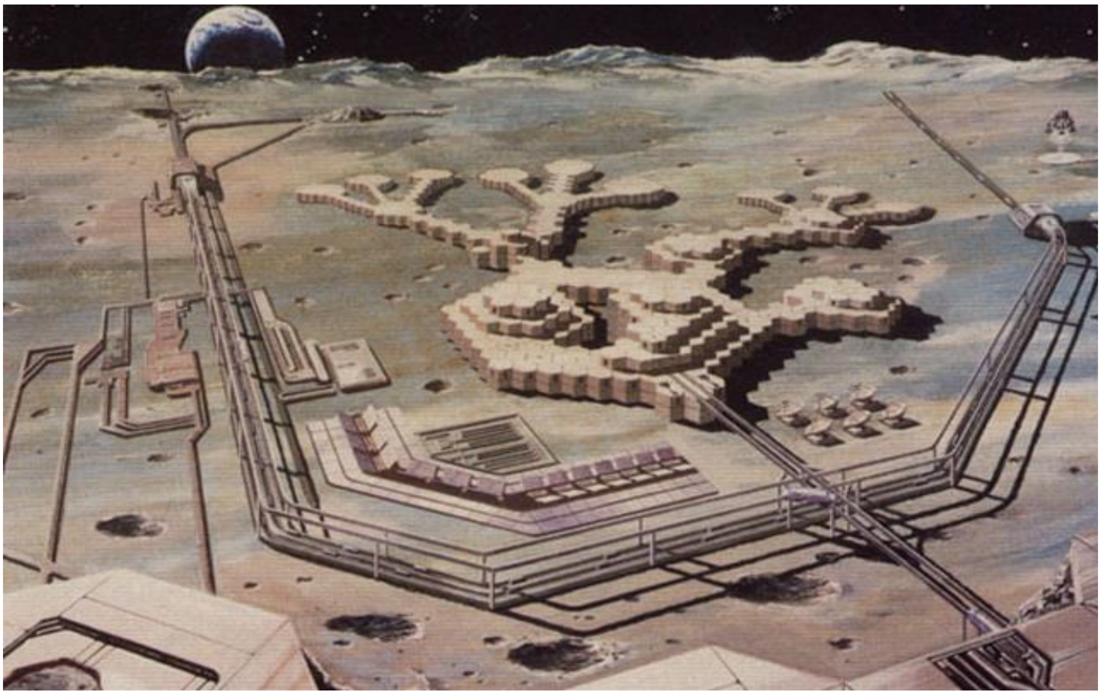


Figure 2.5 Hexagonal Shape Lunar Station Idea

2.2.1.1 Lunar Base Power Supply

For manned missions a continuous power supply will be needed at nights to be survive in Moon conditions. A medium scale lunar base can run with averagely 10 – 15 kw of power to regenerate oxygen, clean the air and recycle water. For this purpose two options can be suggested. One of them is the nuclear energy which can generate big amounts of thermal and electrical energy [37]. Secondly, reflected or albedo radiation can be used from Earth with a power of 0.1 W/m^2 for photovoltaic power generation [65, 66]. Totally 10000 m^2 LILT solar cell array can produce 150 W of power with an average efficiency of 15% on equator region. With using concentration technology it can reach 10 kW of power which is enough for complete a semi – closed life cycle in lunar habitat.

But, although lunar base power supply is one of the most critical aspect of lunar base development, not too many studies have done in the past [39].

2.2.2 SOLAR CELL TECHNOLOGY

2.2.2.1 PHOTOVOLTAICS

Photovoltaics, shortly PV, generates electrical power from semiconductors when photons hits on them. PV technology is a fundamental for solar energy at outdoor operation on Earth or in space for over 30 years. [43] The semiconductor materials have weakly bonded electrons capturing a band of energy called the valence band. When energy getting over a known threshold value, named as bandgap energy, is applied to a valence electron then, the bonds are broken and the electron becomes free to move in a new energy band where it can conduct electricity through the material and this needed energy to free the electron can be supplied by photons. A typical crsytalline solar panel diagram is illustrated in Figure 2.6.

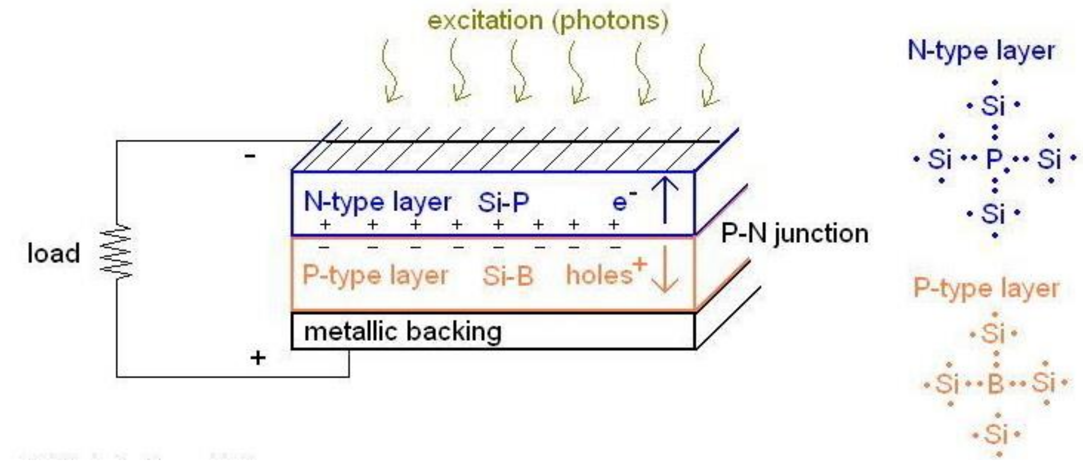


Figure 2.6 A Typical Crsytalline Solar Panel

Today, crystalline silicon (c-Si) solar cells are very popular in market. Also, cadmium telluride (CdTe), amorphous silicon (a-Si), copper indium gallium diselenide (CIGS, Cu(InGa)S2), solar cells are common in use depend on the application types. The concentrator photovoltaics (CPV) are also very popular because of their ability to focus sunlight by concentrators which are made from lenses or mirrors. The main purpose of solar cell technologies is the same. It is aimed to decrease the module costs compared with the dominant Si technology. Other solar cell options are under research such as organic solar cell technology and the new generation solar cells.

The basic equation of maximum efficiency of a photovoltaic cell can be written as 2.1. Here, P_{max} is the maximum output power, E is the radiation of flux and A_{cell} is the area of solar cell.

$$\eta = P_{max} / E * A_{cell} \qquad (2.1)$$

The overall PV solar array efficiencies range from 6% to 25%. Experimental high efficiency solar cells have also been developed, with an efficiency of over 40% [46]. When we consider about solar power efficiency on Earth, it is a fact that; efficiency is highly dependent on the availability of sunshine and seasonal factors (winters have fewer daily hours available for energy production than summers).Weather predictability helps this system to be more efficient.

2.2.2.2 Lunar Environment and Efficiency of a Solar Cell

Sunlight is completely dependable and more intense on Moon. Compared to collectors on Earth, the lunar collectors can have <0.1% the mass per unit area and therefore ultimately be produced faster because the lunar materials and environment are uniquely suited to the production and emplacement of large area and thin film, solid state devices [60, 61]. On the other hand, as discussed before high radiation levels on moon can damage the solar cells and it can decrease the solar cell performance. Therefore, design of solar cells for space applications are very important. The temperature of a solar cell depends on the intensity and duration of its illumination so, the overall effect is a decrease in power of a solar cell with a temperature increase. The Table 2.5. shows the decreases that causes by the proton radiation and high temperature. As seen in table, a silicon cell can have an efficiency value between 40% - 30% due to these effects. Because of the fact that Si solar cells can produce on Moon conditions thanks to lunar soil ingredients, mathematical modeling will be done with using silicon solar cells in Chapter 3.

Table 2.5 Solar Cell Efficiency at Moon [64]

Type of the solar cell	Decrease due to proton radiation E > 30 MeV Fluence 10^{10} /cm^2	Decrease due to high temperature (up to 100°C)	Net decrease estimated	Relative power estimated at moon
Si	20 -25%	40-45%	65%	1
GaAs	5-10%	20-25%	30%	2
Multijunction/ Tandem Group III –V	5-10%	10%	20%	2.3
CIGS	0%	50%	50%	1.4

2.2.2.3 THERMODYNAMIC CALCULATIONS OF LUNAR SOLAR POWER SYSTEMS

2.2.2.3.a Local Entropy Production of Solar Cells

One can get the local entropy production of a solar cell from the formula 2.2. and relation of thermodynamic variables with unit volume can be explained as in 2.3 and 2.4 where " ∇ " is the gradient operator.

$$ds = \frac{1}{T}de - \frac{\mu}{T}dn \qquad (2.2)$$

$$\sigma = \frac{1}{T}\frac{\partial e}{\partial t} - \frac{\mu}{T}\frac{\partial n}{\partial t} + \nabla \cdot \left(\frac{1}{T}j_e - \frac{1}{T}j_\omega - \frac{\mu}{T}j_n\right) \qquad (2.3)$$

$$\sigma = \frac{1}{T}v + j_e\nabla\frac{1}{T} - \frac{\mu}{T}g - j_n\nabla \frac{\mu}{T} + \nabla.(-\frac{1}{T}j_\omega) \qquad (2.4)$$

As seen from the equations, energy generation from subsystem involves in as υ and transfer from the surroundings is explained as ***j*** e ∇ 1/ T. Also, (μg) is the free energy generation in here, the term (***j*** n ∇ μ) is the joule effect and (∇ ***j*** ω / T) is the existence of a gradient pressure. Local entropy equation will be used for proving the thermodynamic consistency of solar cells in below.

2.2.2.3.b Thermodynamic Functions of Radiation

Bose – Einstein factor gives the number of photons in a given mode of radiation [53] by the formula of (2.5) ;

$$fBE = \{\exp[(\varepsilon - \mu)/kT] - 1\}^{-1} \qquad (2.5)$$

and the equation (2.6) gives the grand canonical potential which is related with the equation 2.5.

$$\Omega = kT \ln\{\exp[(\mu - \varepsilon) / kT] - 1\} \quad (2.6)$$

Where,

ε = the photon energy in the mode

k = Boltzmann constant.

And the current densities for the photons can be described as in (2.7);

$$J_n = f_{BE}\, c / (U\, n_{ref}) ; \quad j\, e = \varepsilon f_{BE}\, c / (U\, n_{ref}) ; \quad j\, \omega = \Omega\, c / (U\, n_{ref}) \quad (2.7)$$

In these equations,

c = velocity of light in vacuum

n_{ref} = index of refraction of the medium

The number of photon modes with energy between ε and ε + dε is ;

$$8\pi\, U\, n^3_{ref}\ \varepsilon^2 / (h^3\, c^3)\, d\varepsilon$$

If the modes with energies εm < ε < εM are considered, the total grand canonical potential of the photons, Ω_{ph}, associated with these modes is the sum of the contributions from each mode and will be written as (2.8)

$$\Omega_{ph}\ (U, T, \mu) = 8\, \pi\, U\, n^3_{ref}\ / h^3c^3\ (\mathrm{Int}\ (\varepsilon^2\, k\, T\, \ln\ (1 - e^{(\mu - \varepsilon)/kT}))) \quad (2.8)$$

If we only consider the photons' propagation in a small solid angle dϖ , the grand potential in equation (2.8) must be multiplied by dϖ /4π . The same coefficient affects other thermodynamic variables of the radiation.

2.2.2.3.c Solar Radiation Exergy

Solar radiation exergy can be expressed as;

$$\dot{E}X_{sun} = b = e * U_{ee} \quad (2.9)$$

And the term Solar Radiation Exergy is referred to as the exergy of the Sun and it is the exergy comes from the Sun to any solar system or device [56]. If I(t) is incident solar radiation or energy from the Sun on a known surface area A of the solar device, the energy of thermal radiation (e) can be written as {I(t) * A} and thus the exergy input i.e. radiation exergy (radiation to work conversion) can be described as;

$$\dot{E}X_{sun} = \{ A * I(t) \} * U_{ee} = \{ A * I(t) \} * [1 - 4/3 * (T_o / T_s) + 1/3 * (T_o / T_s)^4] \quad (2.10)$$

T0 = Surrounding temperature in K;
Ts = Sun surface temperature = 6000 K;

2.2.2.4 SOLAR CELL PRODUCTION ON MOON

As mentioned before several types of solar cells can be manufactured on Moon using silicon refined from lunar materials. It is a big advantage for LSP system that thin films are radiation tolerant materials and they includes 0,5 – 25 mm Si in them, naturally. Also, Si is easy to implement on Moon conditions. On the other hand, the biggest disadvantage of Si solar cells is that they are not very strong to stand high temperature differences on Moon and high radiation events are risk factors for them. Nevertheless, more researches should be encouraged on innovative material development technologies. Three important techniques to increase the efficiency of Si solar cells and get over their defects can be listed as follows;

a-) PV concentrated systems
b-) Solar cell cooling and
c-) Magnetic shielding of lunar radiation.

2.2.2.5 PV Concentrated Systems

Concentrator Photovoltaic Technology separates the area for collection of sunlight using optical elements such as mirrors or lenses which directs the light into a much smaller area of solar cells. This permits using high-efficiency but more expensive solar cells since the area of cells is >100 times smaller than the light collection area. The interest in CPV has spread in the last five years when MJ III – V-based solar cells, developed for space applications, started to increase their efficiency [29] but these systems needs an extra cooling system to get a more effective system.

2.2.2.6 Solar Dynamic Systems

Solar Brayton Cycle – The Figure 2.7. indicates the typical Solar Brayton cycle system. In this cycle, concentrating reflector collects the solar energy and focuses the energy into a cavity absorber. Generally, an inert gas is preferred as a working fluid in this system such as argon or helium. When this gas reaches to the absorber, it starts to gain heat because of the inlet conditions of the turbine. After that, it expands into the turbine which drives a compressor and generator and this generator produces electric power. Finally, the working fluid cools where cycle waste heat is transferred to a coolant fluid for rejection to space via a radiator system [50].

The total conversion efficiency of the system approximately differs between 20 % to 35% at turbine inlet temperatures in the 930°C to 1200°C range.

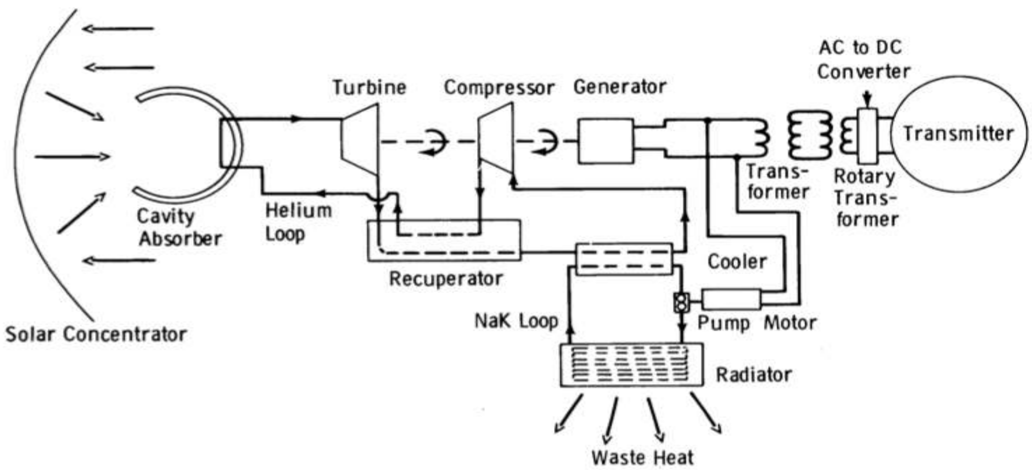


Figure 2.7 Solar Brayton Cycle

Solar Rankine Cycle – Likely with the Brayton cycle, the Rankine cycle collect and focus energy with concentrators into cavity absorbers as seen in the Figure 2.8; But differently from Brayton cycle, a liquid working fluid is used such as water or potassium. The other difference is that hot vapor drives a liquid pump but not like a compressor as in the Brayton cycle. There are several variations of the basic cycle but typical Rankine cycle conversion efficiencies ranges between 15 to 40 % depending upon cycle design.

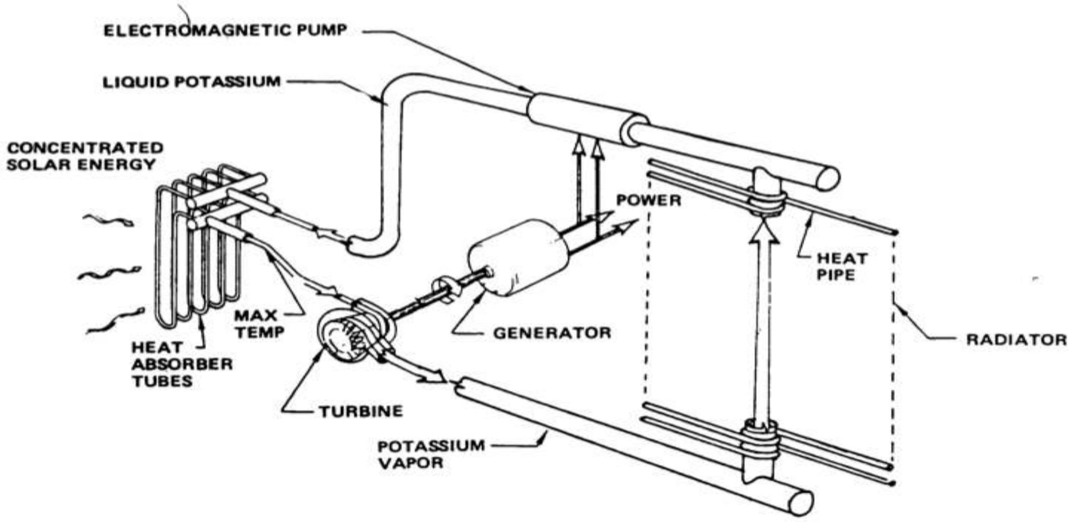


Figure 2.8 Solar Rankine Cycle

2.2.2.7. Magnetic Shielding of Lunar Radiation

Up to now, many approaches have discussed to protect solar arrays from lunar radiation. Covering the solar cells with thick coverglasses is the most easy way for protection. It is easy to apply and it is not an expensive solution. But there is a negative effect of covering cells with coverglasses. It reduces the efficiency of the system. However, to extinguish this negative effect, special design concentrators can be used which are robust to stand Moon conditions as discussed before. Another solution is to produce radiation resistant solar cells. For this purpose several material studies have been done and some of them can be used in space applications.

2.2.3 WIRELESS POWER TRANMISSION TECHNOLOGY

2.2.3.1 MICROWAVE POWER TRANSMISSION

Wireless power transmission has a big role in LSP systems and the inherent nature of the microwave propagation promotes to dual use wireless power beaming and data telemetry applications. On the other hand, for direct microwave wireless power transmission from Moon to the surface of the Earth, a limited range of transmission frequencies are available. Frequencies above 6 GHz are subject to atmospheric attenuation and absorption, frequencies below 2 GHz require excessively large apertures for transmission and reception [51]. The previous studies show that antenna operate with 10 dBi of gain and 18 % bandwidth at 5.8 GHz, and 4 dBi of gain and 3.2 % bandwidth at 2.45 GHz [33]. Also, to provide an efficient transmission the beam should have a Gaussian power density. The component efficiencies are less than for 2.45 GHz, and atmospheric attenuation, particularly with rain, is greater. It was proved that the power transmission efficiency can approach close to 100%. Several models were developed for space solar power transfer by JAXA and NASA, Table 2.6. summarizes these studies.

Table 2.6 Comparison of old WPT Antenna Models

Model	Old JAXA model	JAXA1 model	JAXA2 Model	NASA/DOE model
Frequency	5.8 GHz	5.8 GHz	5.8 GHz	2.45 GHz
Diameter of transmitting antenna	2.6 kmϕ	1 kmϕ	1.93 kmϕ	1 kmϕ
Amplitude taper	10 dB Gaussian	10 dB Gaussian	10 dB Gaussian	10 dB Gaussian
Output power (beamed to earth)	1.3 GW	1.3 GW	1.3 GW	6.72 GW
Maximum power density at center	63 mW/ cm^2	420 mW/cm^2	114 mW/cm^2	2.2 W/ cm^2
Minimum power density at edge	6.3 mW/ cm^2	42 mW/ cm^2	11.4 mW/cm^2	0.22 W/ cm^2
Antenna spacing	0.75 λ	0.75 λ	0.75 λ	0.75 λ
Power per one antenna (Number of elements)	Max. 0.95 W (3.54 billion)	Max. 6.1W (540 million)	Max. 1.7 W (1,950 million)	Max. 185 W (97 million)
Rectenna Diameter	2.0 kmϕ	3.4 kmϕ	2.45 kmϕ	1 kmϕ
Maximum Power Density	180 mW/cm^2	26 mW/cm^2	100 mW/cm2	23 mW/cm^2
Collection Efficiency	96.5 %	86 %	87 %	89 %

2.2.3.1.a Interaction with Ionosphere and Atmosphere

The LSP microwave power beam will affect the Earth's environment in three general areas that are ionospheric heating, atmospheric interactions, and radiofrequency interference. These environmental factors are critical for power transmission characteristics and the cost of the system. This effect is dominant especially in the ionospheric D and E layers. Theoretical studies say that a 5,8-GHz LSP system would be more strongly affected than a 2,45-GHz system [42]. As an example to this, for a cloud temperature of 0°C, and a path length under rain of 4 km, absorption at 5.8 GHz is 0.16 dB, 1.2 dB and 2.8 dB for precipitation rates of 10, 50, and 100 mm/h, respectively [39]. Even rain rates of 100 mm/h are rare [37], it is has to be considered that the Figure 2.9 shows a power loss of almost 50%.

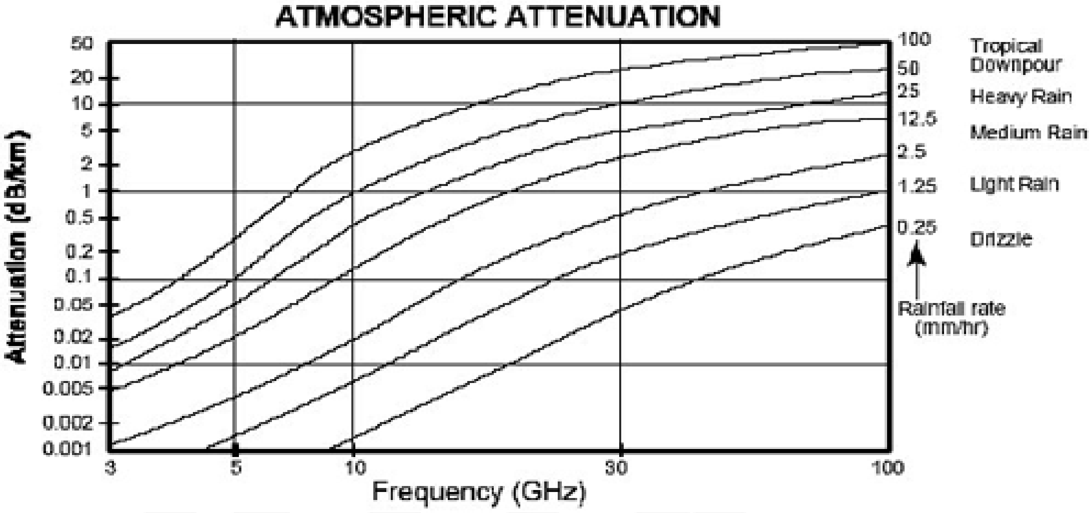


Figure 2.9 Atmospheric Attenuation vs Frequency Diagram

2.2.3.1.b MPT Effects on Human Health

There are lots of considerations about environmental and safety issues during beaming but the corresponding exposure limits for IEEE standards at 2.45 or 5.8 GHz are 81.6 W/m2 and 100 W/m2 averaged over six minutes, and 16.3 or 38.7 W/m2 averaged over 30 minutes [20]. The ICNIRP, the International Commission on Non-Ionising Radiation Protection, and Japan, both apply more drastic limits, they are 50 W/m2 and 10 W/m2 for 2.45 or 5.8 GHz respectively [19]. On the other hand, Criswell prefers < 230 W/ m^2 at the center of the receiver for transmission of commercial power in his calculations and amount of captured energy nearly doubles. Even though, there is not accepted exposure limit for LSP power beaming in Turkey, it is a fact that during power beaming of the LSP established safety limits for microwave exposure are exceeded in an area around and above the rectenna, access would need to be carefully controlled to ensure environmental safety and health standards are maintained. Under normal operation conditions, the LSP system microwave downlink will need to be monitored continuously to secure the firmly tuned phased-array techniques and beam control are functioning correctly.

2.2.3.1.c Transmission and Receiver Antennas

The rectenna which is located on the Earth receives the microwave power from the LSP system and converts this power to dc electricity. The components of a rectenna can be listed as an RF antenna, a low-pass filter, and a rectifier. The efficiency of the system is basically equivalent to its transfer function [48]. The final efficiency (η_{all}) of a microwave power transmission system is the ratio of the DC output power at the receiver end over the DC or AC input power at the transmitter end which is given by the formula;

$$\eta_{all} = \eta_t \eta_c \eta_r \tag{2.11}$$

Here, η_t = transmitter efficiency;

η_c = collection efficiency;

η_r = microwave to electric conversion efficiency of rectennas.

The collection efficiency is proportional to a design parameter τ, which is expressed as Goubau's relation [73,74]

$$\tau = \sqrt{Ar * At} \quad \frac{\lambda}{D} \tag{2.12}$$

Where, A_r = area of the receiver antenna,

A_t = area of the transmitting antenna,

λ = wavelength of the radiation,

D = distance between the transmitting and receiving antennas.

The basic components of a microwave power transmission system are drawn in Figure 2.10. which used for SPS application.

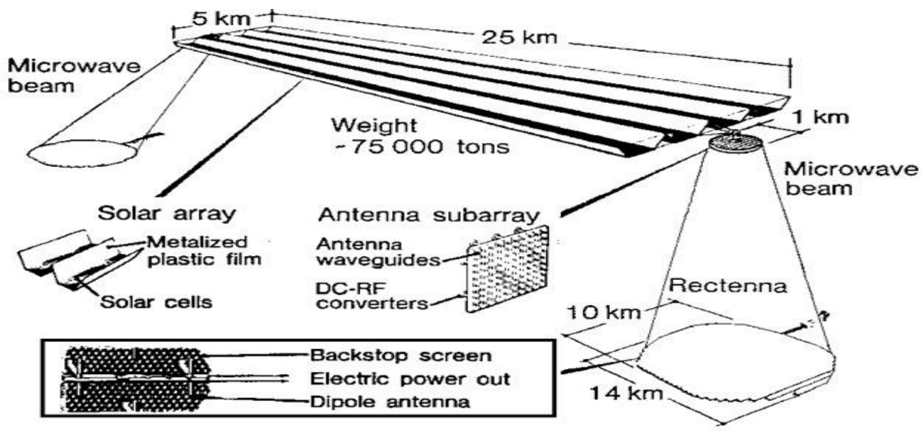


Figure 2.10 Components of a Microwave Power Transmission System

The conversion efficiency of the whole system is the DC power at the receiver end over the AC input power captured by the rectenna also can be written as;

$$\eta_r = P_{out} / P_{in} = (V_{dc}^2 / R_{load}) (1 / P_d A_{eff}) \quad (2.13)$$

As seen in the formula, this conversion efficiency strongly depends on the power density (Pd) distribution across the receiver aperture. In more details, the effective area of the receiving antenna (A_{eff}) can be calculated by using the gain (G_r) and wavelength;

$$A_{eff} = (\lambda_0^2 / 4\pi) G_r \quad (2.14)$$

The maximum incident power density can be derived as follows. Assuming an antenna which has a gain of Gt at the transmitter, the directivity of a system can be obtained from [49];

$$D_0 = 4\pi A_t / \lambda_0^2 \quad (2.15)$$

which means the power of the main beam is magnified by D_0 in a certain direction. Therefore, the maximum power density at the center of an antenna is obtained from;

$$P_d = P_t G_t / \lambda_0^2 d^2 \quad (2.16)$$

Form this equation, one can conclude a higher Pd requires a larger Gt.

Finally, accounting for the free-space reduction in signal strength with distance between the transmitter and receiver, path loss is written (in dB) as;

$$L0(dB) = 20 \log (4 \pi R / \lambda) \geq 0 \tag{2.17}$$

With the definition above we can define the remaining terms of the Friis formula as shown ;

Transmit power	Pt
Transmit antenna line loss	(−)Lt
Transmit antenna gain	Gt
Path loss (free-space)	(−)L0
Atmospheric attenuation	(−)L A
Receive antenna gain	Gr
Receive antenna line loss	(−)Lr
Receive power	Pr

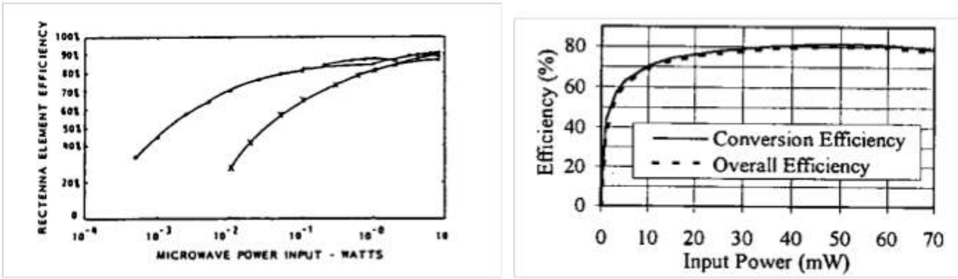
Supposing all of these quantities are expressed in dB or dBm, in the case of Pt, we can write the receive power as;

$$Pr\ (dBm) = Pt - Lt + Gt - L0 - L\ A + Gr - Lr \tag{2.18}$$

2.2.3.1.d Efficiency

In the light of the data from NASA and from the other studies various rectenna schemes have been proposed up to now and the maximum conversion efficiencies anticipated so far are 91.4% at 2.45 GHz and 82% at 5.8 GHz. The RF-DC conversion efficiency of the rectenna is over 80 % of experimental results as shown in Figure 2.11. Decrease of the efficiency is caused by several reasons such as array connection loss, change of optimum operation point of the rectenna array caused by change of connected load, trouble of the rectenna, and any losses on the systems, for example, DC/AC conversion, cables, etc.

It is aimed to get an increase up to % 98 collection efficiency for a LSP system with using a 10dB Gaussian power taper on the transmitting antenna.



(a) Efficiency of 2.45GHz Rectenna[1]   (b) Efficiency of 5.8GHz Rectenna[2]

Figure 2.11 Efficiency of Rectenna Element vs Power Input

2.2.3.1.e Deciding a Receiver Center on Earth

As Criswell's say, thousands of rectennas, totaling approximately 100,000 km^2 in area, are required on Earth to output 20 TWe to customers on Earth [23]. Deserts, industrial centers, or contaminated lands can be used for placing relatively simple rectennas. The potential rectenna sites researches are done computationally over the world and this semi-automatically generated rectenna site list provided in Table 2.7. but it diverges strongly from the manually selected sites. Even though, Turkey is not in the list, it has large areas to place rectennas to get power by LSP systems.

In other respects, the further from the equator a rectenna is sited, the lower the average power intensity of the microwaves that it receives [16]. It is because of the distance increase and angle to the satellite causes the pattern of microwaves on the ground to cover a larger area than for a rectenna exactly on the equator. The general equation of the factor with different latitude can be described as;

$$W_{lat} = \mathrm{Cos}\ (\ lat * 10{,}94 * \pi / 180\ ) \tag{2.19}$$

W_{lat} = factor with the different latitude
lat = the latitude of the rectenna site in degrees.

In this equation, the coefficient 10.94 is a mathematical factor value to show the effect of the latitude changes on Earth.

Table 2.7 The Potential Rectenna Sites Over the World [57]

N	Lat. N	Lon. E	Merit (reverse payoff time)	Location	Solar potential, TW
1	24.25	118.50	9591	Kinmen, Taiwan	5.300
2	28.25	86.00	9124	Bungamati, China-Nepal border	7.600
3	30.50	80.75	8167	Burang, China-India border	4.900
4	-3.75	112.00	7276	Sampit, Indonesia	7.000
5	21.50	93.00	6537	Paletwa, Myanmar	9.600
6	-3.25	106.25	6348	TulungSelapan, Indonesia	5.900
7	27.75	92.00	6128	Tawang, China-India border	7.800
8	13.75	104.50	5356	KulenPromtep, Cambodia	8.200
9	-9.00	114.50	5048	Kendalrejo, Indonesia	1.900
10	28.25	34.50	4937	Sharm el-Sheikh, Egypt	6.400
11	27.00	71.25	4538	Jaisalmer, India	8.200
12	5.50	101.50	4458	Hulu Perak, Malaysia	6.900
13	2.00	32.00	4451	Kabarega National Park, Uganda	15.800
14	32.00	69.25	4152	ZarghunShar, Afghanistan	3.800
15	27.00	29.25	4102	West of Asyut, Egypt	8.700
16	-3.00	38.25	4037	Tsavo West National Park, Somalia	9.000
17	33.50	132.25	4027	Sadamisaki Peninsula, Japan	0.520
18	15.00	118.00	3593	Scarborough Reef, Philippines (disputed)	2.200
19	3.50	36.75	3582	Lake Turkana, Kenya	14.500
20	18.50	104.50	3474	Bolikhamsai, Laos	10.700
21	34.00	139.50	3461	Izu islands, Japan	0.035
22	-20.25	-46.50	3424	East of Uberaba, Brazil	9.400
23	29.25	101.00	3251	Garze, China	7.000
24	7.50	11.25	3009	Gashaka-Gumti National Park	12.500
25	11.25	35.50	???	Benishangul-Gumuz, Ethiopia	10.000

2.2.3.1.f Site Selection in Turkey

Turkey lies between latitudes 35° and 43°N, and longitudes 25°and 45°E. Because of the fact that it is between the coordinates 60º N and 60º S, it may receive the power from the moon approximately 8 hours in a day without installing any other relay stallites. But getting a 7/24 continues energy via lunar solar power systems we need relay stallites to direct the microwave or laser power to the rectenna in Turkey. Considering the latitude effect, rainfall rate and topographical properties of the cities in Turkey, this receiver center may establish in Konya, Ankara or Gaziantep would have a rectenna diameter 2,245 km for 5,8 GHZ which will cover approximately 3,95 km^2 on ground with a transmitter antenna diameter 20 km on Moon.

Gaziantep locates at the junction point of the Southeastern Anatolia Region and Mediterranean region and lies between 36 ° 28 'and 38 ° 01' east longitude and 36 ° 38 'and 37 ° 32' north latitude. It is in the 4^{th} degree earthquake zone. The distribution of landforms with an altitude of 855 meters in city lands are as follows; mountains of 51.9%, plains 26.9% the plateaus 19.0%, highland is 2.2% [52]. Annual rainfall of 552,7 kg / m². The number of rainy days in Gaziantep was measured as 86 days [28].

Ankara is the capital city of Turkey. It is located in the central part of the country, Central Anatolia. It lies between the 39.92° latitude and 32.86° longitude coordinates [67]. Steppe climate is dominant in Ankara and therefore the summers are warm and dry and the winters are cold and snowy. The rain season is spring, especially May. Annual rainfall of the city is 402,2 kg / m². The number of rainy days in Ankara was measured as 104 days [28].

Konya city is in the southern part of Middle Anatolian. With an area of 41.001 km^2, Konya is the largest province in Turkey. The Latitude and Longitude of Konya is 37.8667 and 32.4833 respectively. It has a mid-latitude steppe/ semi arid cool climate. Annual rainfall of the city is 318,7 kg / m². The number of rainy days in Ankara was measured as 83,5 days [28].

On the other hand, there is no detailed academic researches about air traffic density of these cities, it must be studied in detail in the next studies. Also, only topographic and rainfall rates are concerned while deciding the city to construct a receiver center, for a more healthy analysis, politics, army and other special issues must be concerned. The beams should be constantly formed, shut off, and reformed as Earth, the Moon, and satellites move with respect to one another.

2.2.3.2 LASER POWER TRANSMISSION

The other option for wireless power transmission is laser technology, in the case of electromagnetic radiation closer to the visible range of the spectrum power can be transferred by converting electricity into a laser beam. Special kind of photovoltaic laser power converters which are optimized for monochromatic light conversion are used at the receiver [55]. Most commonly gallium arsenide (GaAs) and crystalline silicon (Si) [47] in use with current solar photovoltaic space power systems.

2.2.3.2.a Safety Issues

One of the most famous guideline ICNRP explains that type of limits can differ from 50 to 10 W/m2 for occupationally exposed vs. the general public, at either frequency [19]. The Table 2.8 shows the legal limits for laser and microwave beaming.

Table 2.8 Legally-Defined EM Exposure Upper Limits

Type of Limit	Laser	Microwave
Typical General Population / Cautionary Safety Limit	n/a	< 1-10 Watts / m^2
Typical Employee Safety Limits (Incidental Exposure / Viewing)	< 10 Watts / m^2	< 100 Watts / m^2
Typical General / Eye Safety Limit for Long Durations (>10 min)	< 25 Watts / m^2	n/a
Typical General / Eye Safety Limit for Short Durations (>10 sec)	< 50 Watts / m^2	n/a

Because of the fact that it could be a hazard to flight aided by the use of night vision goggles and a beam of several hundred kW of infrared radiation could blind night vision systems [41], Laser power transmission needs significant safety systems and reasonable population standoff distances for the receiving locations.

2.2.3.2.b Atmospheric Attenuation

Atmospheric losses depend on the path length through the atmosphere and get increase exponentially with it but for zenith angles less than 60° and 85% zenith transmission, the trajectory-averaged losses will be larger than the zenith losses by a factor of only 1.2 – 1.5. Differently from the Yag lasers, at 1.08 µm, loss in the atmosphere is dominated by particulate scattering. Also, it is calculated in the previous studies that the overall transmission for YAG lasers which has a wavelength 1.06 µm, vertically from sea level to 150 km as 0.73 for year-round average conditions in the Sea of Japan, but it must be noted that the transmission from 3 km altitude would be greater than 0.9.

We assume a land site can be found with vertical transmission of 0.85 or better under most clear-sky conditions such as Mediterranean.

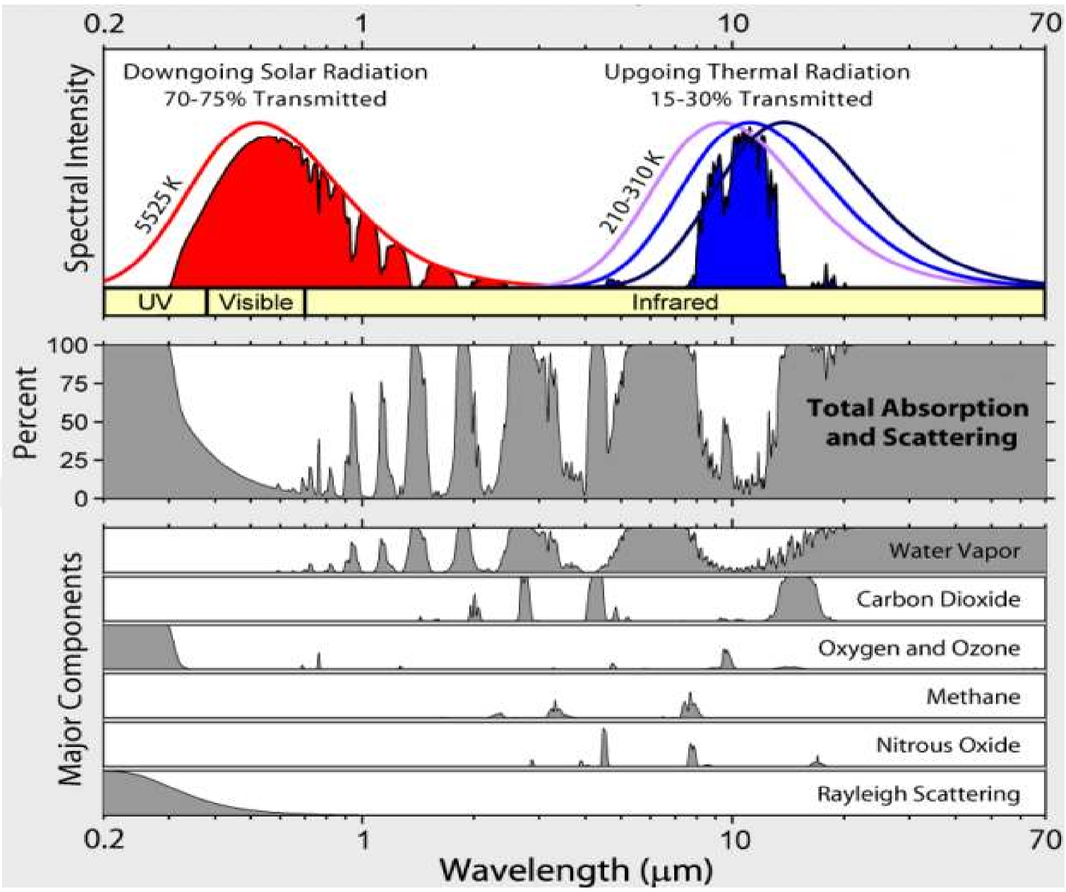


Figure 2.12 Radiation Transmitted through the Atmosphere (From Rohde, 2007)

2.2.3.2.c Efficiency

Increasing the efficiency of converting electricity to laser light has great importance for laser power transmission systems and recent work on diode lasers has achieved 60% electrical to light efficiency for a laser pumping diode bank [38]. Even though the >60% conversion efficiency reported for diode pump power at 1.06 μm laser light conversion in a Yb:YAG laser [44] suggests overall conversion efficiency approaching 40% but still this value is comparatively smaller than the microwave power transmission efficiency. Solar pumped lasers can be an alternative to diode-pumped lasers which give direct conversion from sunlight to laser light. The current solar-pumped laser efficiency record is held by Nd:YAG at 4.8% [45].

2.2.3.2.d Transmission and Receiver Facilities

There are three main factors that are important while installing a laser power transmission facility in the context of transmitting big amounts of energy in GW or TW. The first one of these factors is the amount of power that a laser, which could be integrated into the architecture, could be expected to produce. This factor can vary widely from a few MW to many TWs depending on the technology selected. The second factor is the electrical to optical efficiency. This factor also varies widely depending on the technology used to generate and control the laser beam. The third factor is that of loss and beam spread over distance. This factor can be modeled by examining the effect on the laser beam of the media through which the laser is transmitted.

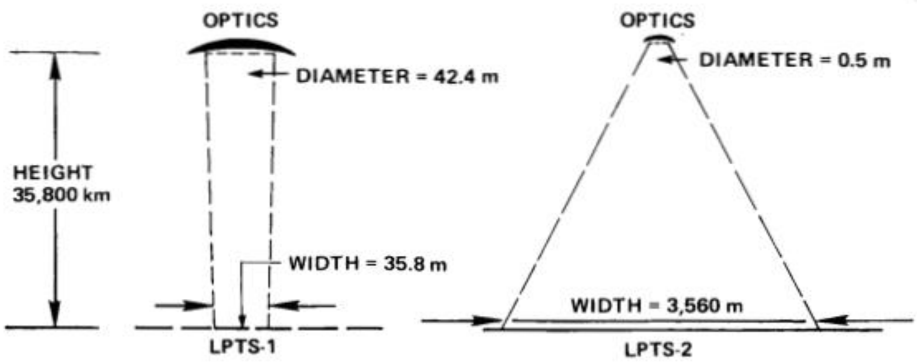


Figure 2.13 Example Optics and Beam Characteristic of a LPTS Concept

The effective design of a refractive element assembly is a key a challenge for laser power transmission systems and it must reduce absorption of radiation by the element and provide for the removal of waste heat to avoid excessive beam distortion. Also, it is important to develop components which are capable of low-loss, high power-density transmission and reflection of laser light. Fresnel lenses are good options for this purpose and they shaped like a dart board, with concentric rings of prisms around a lens that's a magnifying glass. All of these features let them focus scattered laser beam from the laser facility on Moon into a tight beam on Earth, also using concentrator mirrors then it will converted into electricity via photoelectric converters.

Considering the all the information above, receiver facility should locate in equator regions to get the power from moon more effectively. Also because of the fact that there is little cloud cover in sky in equator regions, transmission efficiency of the laser power cannot be affected from the atmosphere conditions too much. In this point of view the laser receiver facility may install in Mediterranean Sea in the borders of Turkey but of course, serious studies must be done before taking such a decision. Military, politic, environmental and health issues must be discussed.

CHAPTER 3

MATHEMATICAL AND COMPUTATIONAL MODELING OF LUNAR SOLAR POWER SYSTEMS

In this chapter of thesis, a mathematical and computational model is designed to get 20 TWe of energy on Earth to meet the energy demand of the world by the year 2050, in a safe and environmental manner. The macro parameters of a lunar solar power system and equivalent efficiency values are listed. Main purpose is to get same results mathematically and computationally under the same conditions. The final power on Moon to get 20 TWe on Earth by using different types of solar cells and number of these cells along the lunar equator, total covered area on Moon and width of the solar belt, also, diameters of the transmitter and receiver antennas will be calculated to decide the best options for a lunar solar power system. Furthermore, at the first page of the program, it is aimed to get graphical result due to the selections of the user in bold and thinner graphs for the other solar cell options to compare the efficiency easily. At the second page of the program, annual net power graph will be drawn due to the cities. The program will take the statistical data from the official web page of the Meteorology General Management of Turkey.

3.1 MATERIAL AND METHODOLOGY OF THE SYSTEM

Establishing and maintaining a 20 TWe LSP System is a far larger activity than the LSP Demo Base [22]. The Table 3.1, gives operating assumptions that scale the size of a 20 TWe LSP System. There are lots of parameters that affect the design of a LSP system but for simplicity, it is accepted that the most important factors are transmission type, frequency and wavelength selection, solar panel type, concentration rate and weather condition on Earth.

Assumptions;

1) There is one microwave power transmission facility and one laser power transmission facility on Moon, one can select MPT or laser transmission type but in mathematical calculation power will send by MPT technology.

2) In both calculations, the distance from Moon to Earth is taken as H = 380,000 km and the diameter of the Moon equator, D = 11,000 km. It is assumed that the transmission facilities are installed in equator region of the Moon which is always face to Earth and receiver facilities are located in equator region on Earth.

3) In mathematical calculation, the weather is assumed as clear sky but computationally, user can decide the weather condition on Earth. There are four options for MPT as clear weather, light rain, medium rain and heavy rain and two option for laser as clear weather and heavy fog because of the reasons that explained in chapter 2 but it is accepted that computationally selected weather condition does not change for 8 hours for simplicity.

4) It is assumed that there will be no any relay satellite or orbital mirrors and redirectivity of the beams will not be calculated. So, in this way a facility in equator region can get the power during only 8 hours in a day without any external system.

5) For MPT, both in mathematical and computational calculations it is assumed that the magnetron is used as microwave vacuum tube with the efficiency 90 % and antenna spacing is 0,75 λ, amplitude taper 10 DB Gaussian but computationally, one can increase the efficiency of the system up to % 99 to compare how much it affects the antenna sizing.

6) Latitude values are taken as 37,05° for Gaziantep, 37,52° for Konya and 39,57° for Ankara.

7) If the monthly average rainfall rate of one city is above the 80 kg/ m^2, it will be assumed as the weather is between the heavy rain and medium rain as the number of rainy day in one month, if the monthly average rainfall rate is between 80 kg/ m^2 and 40 kg/ m^2, the weather is accepted as medium rain and light rain, else it is below the 40 kg/ m^2, it will be assumed as the weather is between clear sky and light rain.

Table 3.1 Macro Parameter of a Lunar Solar Power System [23]

PARAMETER	SYMBOL	BASELINE (2025)
Scale Factors		
Final Power on Earth	P_{final}	20 (TWe)
Construction Time	T_{cons}	30 yr
Manned and Unmanned Team Work Hour	$T_{operation}$	24 hr
Number of Power Transmission Bases for MPT	N_{MPT}	1
Number of Power Transmission Bases for Laser	N_{Laser}	1
Beam Intensity for MPT	I_{MPT}	100 W / m^2
Beam Intensity for Laser	I_{Laser}	10 W / m^2
Beam Wavelenght for MPT	λ_{MPT}	5,8 GHZ^{-1}
Beam Wavelenght for Laser	λ_{Laser}	1,06μm
Solar Power in Free Space	P_{Sun}	1,370 W / m^2
Lunar Ecilipse Impact	$N_{ecilipse}$	99,9 %
Lunar Radiation Effect	N_{rad}	0,90 %
Lunar Dust Effect	N_{dust}	0,99 %
Solar Concentration Rate	SC	3
Solar Concentration Efficiency	N_{SC}	95 %
Thermal Efficiency of Rankine Cycle	N_{th}	93 %
Surface Transmission Efficiency on Moon	N_{sur}	99 %
Solar Cell Efficiency of Silicon	$N_{Si-Cell}$	40 %
Fill Factor	FF	1
Area of the Silicon Solar Cell	A_{cell}	70 cm^2
Electric Power Collection Efficiency	$N_{Collect}$	98 %
Earth Atmospheric Transmission Efficiency	N_{atm}	99 % (Clear)
DC to Microwave Efficiency	N_{DC-Mw}	92 %
DC to Laser	$N_{DC-Laser}$	40 %
Rectifier Antenna Efficiency	N_{R-A}	90 %
Transmitter Antenna Efficiency	N_{T-A}	96 %
Microwave to DC	N_{RF-DC}	95 %
Laser to DC	$N_{Laser-DC}$	80 %
Operating Rate	OP	100 %

3.1.1 Design Steps of the Matlab Interface

The Matlab Gui 2011 version is used to create the application with graphical user interfaces in Matlab. The application consists of two pages, the first page is for energy and efficiency calculations of the whole system and the second page is designed for antenna calculations. The pop – up menu and push button properties of the program are used while creating the pages.

At the first page, it is aimed to get a linear graph of final power to total area on Moon in bold for selected solar panel type due to the other selections and thinner graphs for non- selected solar panel types to compare easily the efficiency of the solar panel types under same conditions to get 20 TWe of energy on Earth. Result boxes are located under the graph for just selected circumstance to show the final power on moon, number of needed solar panels, total covered area on Moon and width of the Lunar belt. The first pop – up menu on the first page is energy transmission type. User can select microwave power transmission type or laser power transmission type. If one select Microwave power transmission, second pop – up menu for wavelength selection is allowed and frequency selection is unable to use. It is vice versa for the laser power transmission. Here, there are two options for microwave power transmission as 2,45 Ghz^{-1} and 5,8 Ghz^{-1}. However, there is just one option for laser power transmission as 1,06 nm. Because of the fact that the efficiency values differ for 2,45 and 5,8 and laser options, all the variables are introduced to the program as in Table 3.2 and for further optimizations, two menu are allocated for transmitter antennas and receiver rectennas.

Table 3.2 Atmospheric Efficiency List for the Energy Transmission

λ = 2,45 GHZ^{-1}	λ = 5,8 GHZ^{-1}	Laser
N_{clear} = 0,999	N_{clear} = 0,999	N_{clear} = 0,85
N_{light} = 0,990	N_{light} = 0,980	N_{fog} = 0,80
N_{med} = 0,985	N_{med} = 0,950	
N_{heavy} = 0,980	N_{heavy} = 0,900	

```
ConcentrationRate = get(handles.popupmenu8,'Value');
TypeOfCell = get(handles.popupmenu4,'Value');
Weather = get(handles.popupmenu5,'Value');
Frekans = get(handles.frekans,'Value');
Lambda = get(handles.dalgaboyu,'Value');
b = get(handles.popupmenu2,'Value');
c = get(handles.popupmenu3,'Value');
if (Lambda==2)
    Nrfdc = 0.92;
    Nra = 0.96;
    Nta = 0.98;
    Ndcrf = 0.96;
    TW = 10^12;
    Pfinal = 20 * TW;
end
if (Lambda==3)
    Nrfdc = 0.9;
    Nra = 0.9;
    Nta = 0.96;
    Ndcrf = 0.95;
    TW = 10^12;
    Pfinal = 20 * TW;
end
```

Figure 3.1 Efficiency Differences between λ=2,45 and λ=5,8 GHZ

Then, user can decide the concentration rate of the solar panels. Three options are given to user as 1, 2 and 3. If it is 1, it means there is no concentration. For 2 and 3 rates, it is automatically accepted that there is a cooling system up to 100^0 and the efficiencies of the solar panels changes due to theoretical studies which is explained in chapter 2 and as in Table 2.5**.** Finally, user decides to solar panel type and weather condition on Earth. Also here, the efficiency values of solar panels are accepted as in Table 2.5.

At the second page of the program, first of all it calculates the design parameter. Then one decides the wavelength as in page 1 and the intensity of the beam in the options of 100 W/m^2, 230 W/m^2 and 300 W/m^2. Even though, IEEE standards allow up to 100 W/m^2 at the center of the receiver antennas on Earth, Criswell prefers 230 W/m^2 and some Japan scientists take it as 300 W/m^2 in their calculations. There is no legally accepted value for beam intensity in Turkey for MPT and so, user can decide it computationally. Finally user decides the city for the construction of a receiver center in the options of Konya, Ankara and Gaziantep. The latitude value and rainfall rate changes due to the city selection. The program take the statistical data from the official web page of the Meteorology General Management of Turkey.

https://www.mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx?m=GAZIANTEP

Resmi İstatistikler

İllerimize Ait İstatistik Verileri | Meteorolojik Parametrelerin Türkiye Analizi | TUMAS | Haber Bülteni | İklim Metaveri | Yayınlarımız | Duyurular | Bakanlık
Resmi İstatistik Portalı | Ulusal Veri Yayınlama Takvimi

GAZIANTEP	Ocak	Şubat	Mart	Nisan	Mayıs	Haziran	Temmuz	Ağustos	Eylül	Ekim	Kasım	Aralık	Yıllık
	Uzun Yıllar İçinde Gerçekleşen Ortalama Değerler (1950 - 2015)												
Ortalama Sıcaklık (°C)	3.0	4.3	8.1	13.2	18.6	24.0	27.7	27.4	22.8	16.1	9.3	4.8	14.9
Ortalama En Yüksek Sıcaklık (°C)	7.6	9.4	14.0	19.7	25.4	31.1	35.3	35.3	31.1	24.2	16.1	9.8	21.6
Ortalama En Düşük Sıcaklık (°C)	-0.8	0.0	3.0	7.3	11.8	17.0	21.1	20.9	16.2	10.0	4.4	1.0	9.3
Ortalama Güneşlenme Süresi (saat)	3.4	4.3	5.4	7.1	9.0	10.6	11.6	10.3	9.1	7.2	5.3	3.4	86.7
Ortalama Yağışlı Gün Sayısı	12.9	12.4	12.0	10.3	7.3	2.2	0.6	0.5	1.5	6.3	8.5	12.0	86.5
Aylık Toplam Yağış Miktarı Ortalaması (kg/m2)	96.6	84.0	73.5	53.4	32.7	6.7	2.5	2.2	5.8	36.2	63.0	96.1	552.7
	Uzun Yıllar İçinde Gerçekleşen En Yüksek ve En Düşük Değerler (1950 - 2015)*												

Figure 3.2 Official Web Page of the Meteorology General Management of Turkey

As seen in Figure 3.2, at this web page one can reach all the weather statistics for a selected city in Turkey. When the user decides the city on the interface of the Matlab screen, the program connects this web page on internet. It takes only the average rainy day column and monthly total rainfall rate column. It rounds the day value to upper integer number and checks the average rainfall rate and decides the interval of the weather. After that, it gives random N_{atm} values between these intervals up to rainy day number, then it subtracts rainy day number from total day number of the month and gives random N_{atm} values between clear and light rain intervals. Finally it calculates the P_{net} value for each N_{atm} value as the formula below;

$$P_{net} = P_{total} * N_{atm} * W_{lat} \tag{3.1}$$

3.2. MATHEMATICAL CALCULATIONS

Assuming that a LSP unit will generate 20 TW effective power on Earth, and will send of the power by microwave power transmission system, the characteristic efficiencies listed in Table 3.1. The final output power from the solar cells can be calculated from the formula [36];

$$P_{final} = P_{f-SC} \left(\eta_{RF-DC} \text{ x } \eta_{R-A} \text{ x } \eta_{atm} \text{ x } \eta_{T-A} \text{ x } \eta_{DC-RF} \right) \tag{3.2}$$

$$P_{f-SC} = 20 \text{ TW} / (0,90 \times 0,96 \times 0,98 \times 0,90 \times 0,90)$$
$$P_{f-SC} = 29,16 \text{ TW}$$

So, one needs to collect 29,16 TW of power on Moon to get 20 TW of power on Earth. Using concentrated silicon solar cells with an efficiency 40 % and an area 70 cm^2, the produced power from one cell can be calculated as [36];

$$P_L = \text{Solar Constant} \times \text{Concenration Rate} \times \eta_{Cell} \times A_{Cell} \qquad (3.3)$$

$$P_L = (0,1373 \text{ W} / \text{cm}^2) \times 3 \times 0,40 \times 70 \text{ cm}^2$$
$$P_L = 11,53 \text{ W / Cell}$$

Taking into the account of hard lunar conditions like lunar dust and lunar radiation, also thermal efficiency of the cooling system;

$$P_{Cell} = P_L \times (\eta_{Rad} \times \eta_{Dust} \times \eta_{th} \times \eta_{Other}) \qquad (3.4)$$

$$P_{Cell} = 11,53 \times 0,90 \times 0,99 \times 0,93 \times 0,99$$
$$P_{Cell} = 9,45 \text{ W / Cell}$$

It means that, one cell on Moon can generate 9,45 W under assuming conditions. So, the number of cells to generate 29,16 TW;

$$N_{Cell} = P_{f\text{-}SC} / P_{Cell} \qquad (3.5)$$

$$N_{Cell} = 29,16 \times 10^{12} \text{ W} / 9,45 \text{ W Cell}^{-1}$$

$$N_{Cell} = 3,08 \times 10^{12} \text{ Cell}$$

It covers the surface area $A = 3,08 \times 10^{12} \times 70 \text{ cm}^2 / 10000 \text{ m}^2 = 2,16 \times 10^{10} \text{ m}^2$ on Moon but we should multiply it with 2 because of the day – night cycle. The lunar equator of the Moon D = 11,000 km, that one can find the width along the lunar equator from the formula;

$$W = 2,16 \times 10^4 \text{ km}^2 * 2 \; / \; 11,000 \text{ km} = 3,92 \text{ km}$$

The surface area of the Moon is $37,9 \times 10^6$ km^2 (see Table 2.2.) and $4,32 \times 10^4$ km^2 is the 0,113 % of the total Moon surface area.

Before defining the rectenna characteristics, we should decide the power flux at the center of the receiver antenna. Even though different values are allowed computationally, here, a conservative value is selected. It will be 100 W/m^2 which is less dangerous from a biological point of view and at the edge of the receiver will be nearly 10 W/m^2 for safety reasons, which are discussed in chapter 2, for λ = 5,8 GHZ^{-1} one can calculate the antenna sizing for receiver and transmitter antenna as follows;

$$\eta_b = 1 - \exp (- \tau^2) \qquad (3.6)$$

For η_b = 0,96 , f = 5,8 GHZ = > $\lambda = 5,168*10^{-5}$ and H = 380,000 km;

$$0,96 = 1- \exp (- \tau^2)$$
$$\tau = 1,794$$

$$\tau = \pi D_T D_R \; / \; 4 \lambda H \qquad (3.7)$$

$$\tau = 1,794 = 3,14 D_T D_R / 4 * 5,168*10^{-5} * 380,000$$

$$D_T D_R = 44,88 \text{ km}^2$$

If D_T = 20 km;
D_R = 2,24 km and R_R = 1,12 km, Area of the receiver antenna A_R = 3,95 km^2.

So, according to the calculations the diameter of the receiver center on Earth should be 2,24 km and the total area should be 3,95 km^2.

For maximum beam intensity at the center 100 W / m^2, P_{total} would be 395 MW and for 230 W / m^2 , P_{total} would be 908,85 MW.

For the calculation of P_{net} value for Gaziantep, one needs the latitude value of the city and it is accepted as 37,05° and from the formula of latitude effect;

$$W_{lat} = \cos (37{,}05 * 10{,}94 * \pi / 180)$$
$$W_{lat} = 0{,}9923$$

For a clear sky in Gaziantep;

$$P_{net} = P_{total} * W_{lat} * N_{atm} \quad (3.8)$$

$$P_{net} = 908{,}85 * 0{,}9923 * 0{,}99$$
$$P_{net} = 901{,}03 \text{ MW}$$

CHAPTER 4

COMPUTATIONAL RESULTS

4.1 ENERGY AND EFFICIENCY CALCULATIONS

1) Selected; Silicon cell, clear weather, no concentration, microwave transmission, $\lambda = 2{,}45\ GHZ^{-1}$.

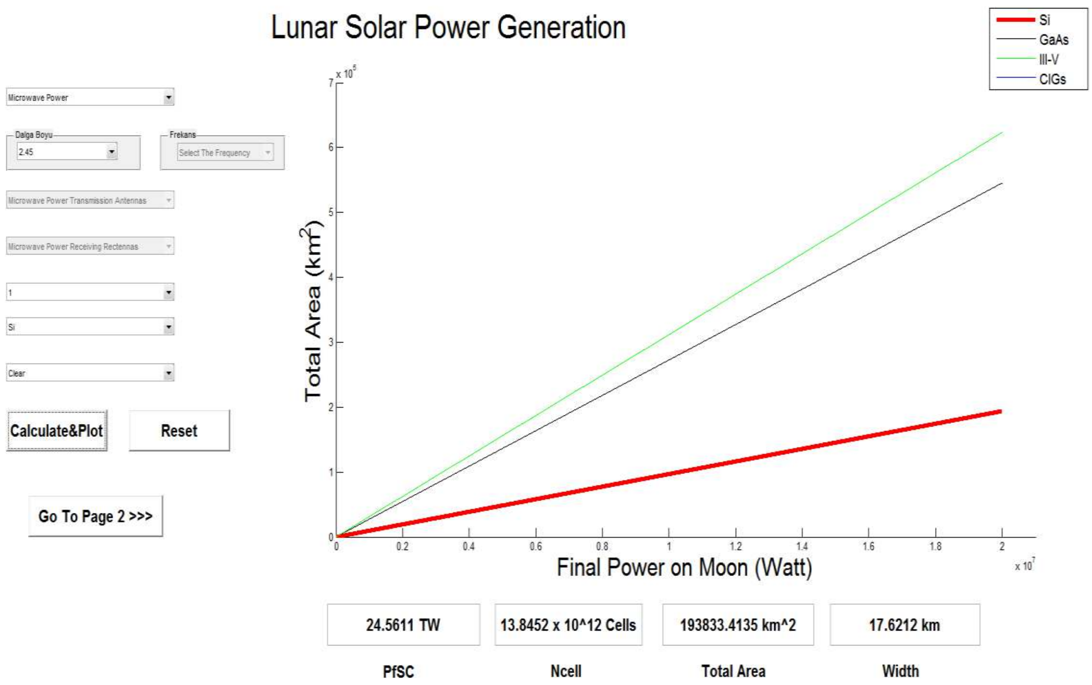


Figure 4.1 MPT, $\lambda = 2{,}45\ GHZ^{-1}$, Si, Clear, No concentration

2) Selected; Silicon cell, clear weather, concentration rate 3, microwave transmission, $\lambda = 2{,}45\ GHZ^{-1}$.

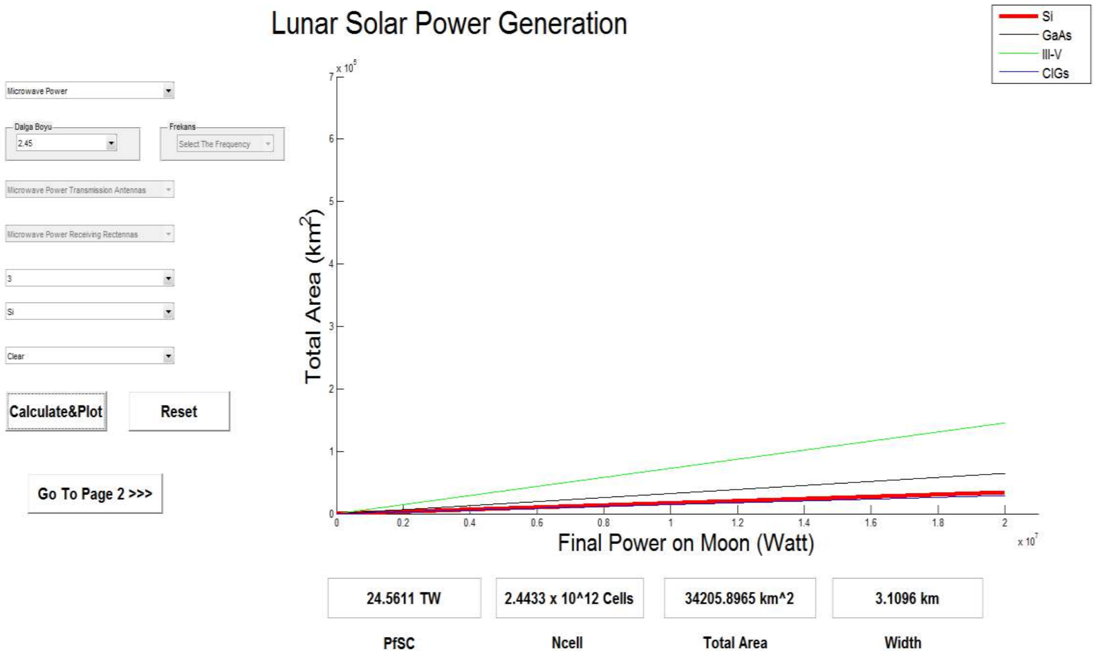


Figure 4.2 MPT, $\lambda = 2{,}45\ GHZ^{-1,}$ Si, Clear, Concentration 3

3) Selected; Si cell, clear weather, concentration rate 3, microwave transmission, $\lambda = 5{,}8\ GHZ^{-1}$.

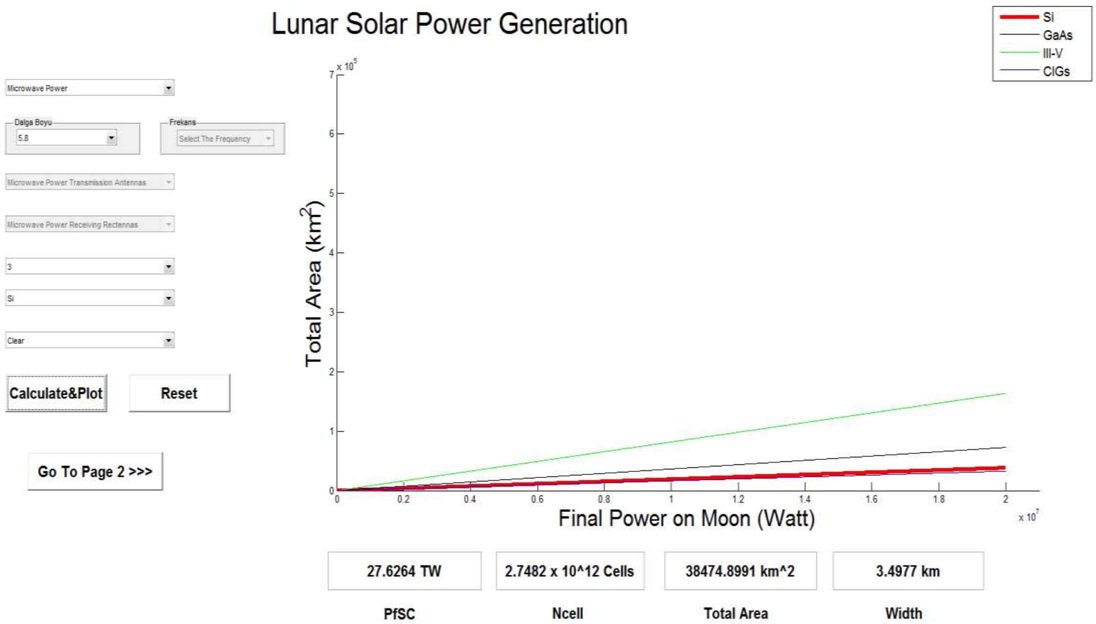


Figure 4.3 MPT, $\lambda = 5{,}8\ GHZ^{-1,}$ Si, Clear, Concentration 3

4) Selected; CIGS cell, clear weather, concentration rate 3, microwave transmission, λ = 5,8 GHZ^{-1}.

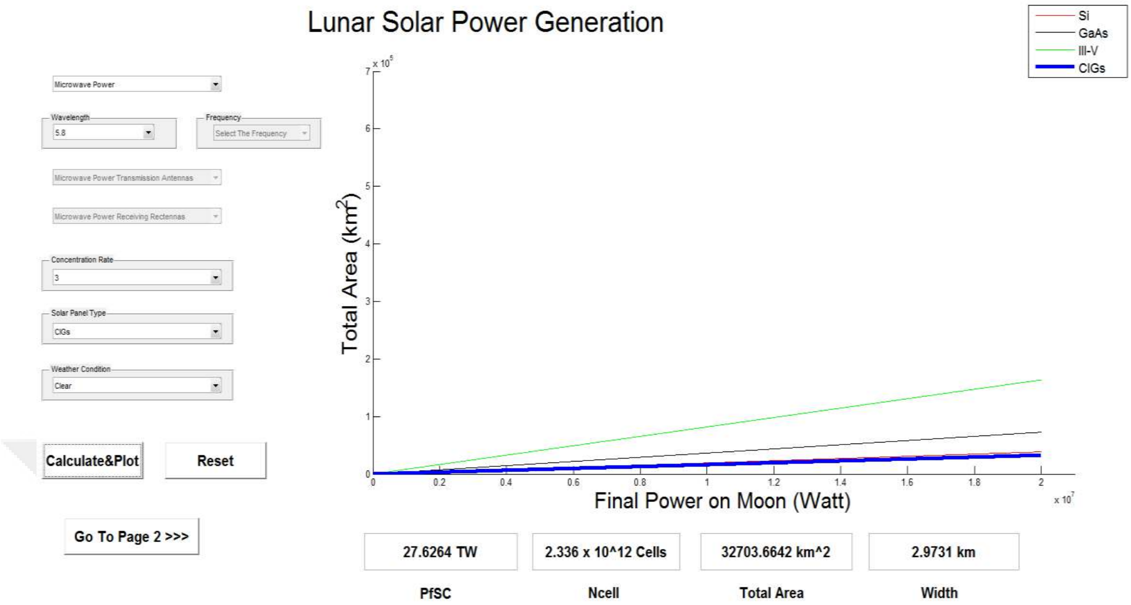


Figure 4.4 MPT, λ = 5,8 GHZ^{-1}, CIGS, Clear, Concentration 3

5) Selected; GaAs cell, clear weather, no concentration, microwave transmission,

λ = 5,8 GHZ^{-1}.

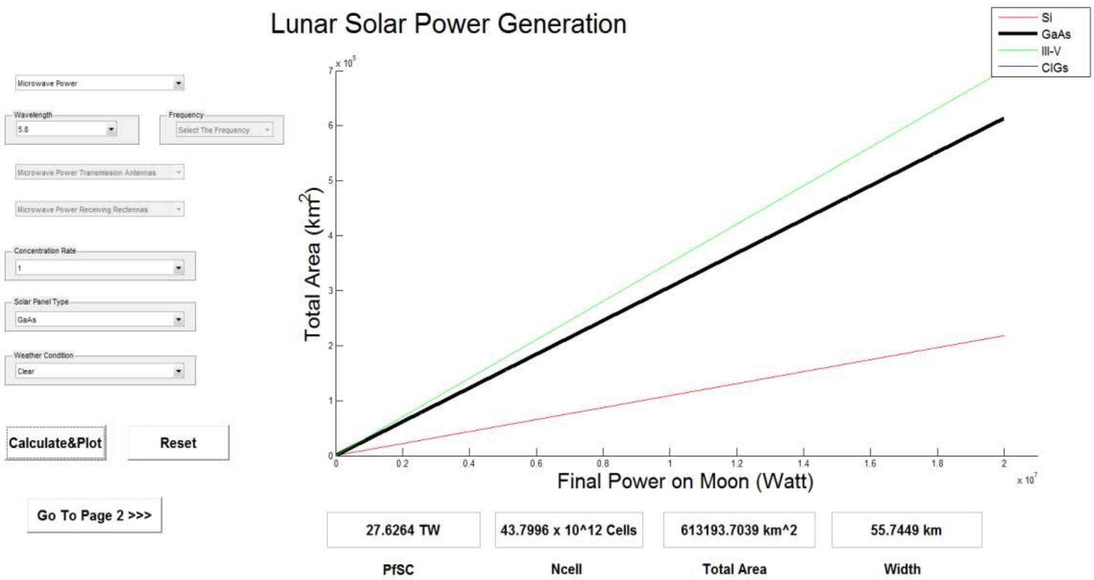


Figure 4.5 MPT, λ = 5,8 GHZ^{-1}, GaAs, Clear, No concentration

6) Selected ; Multijunction III – V, clear weather, no concentration, microwave transmission, λ = 2,45 GHZ^{-1}

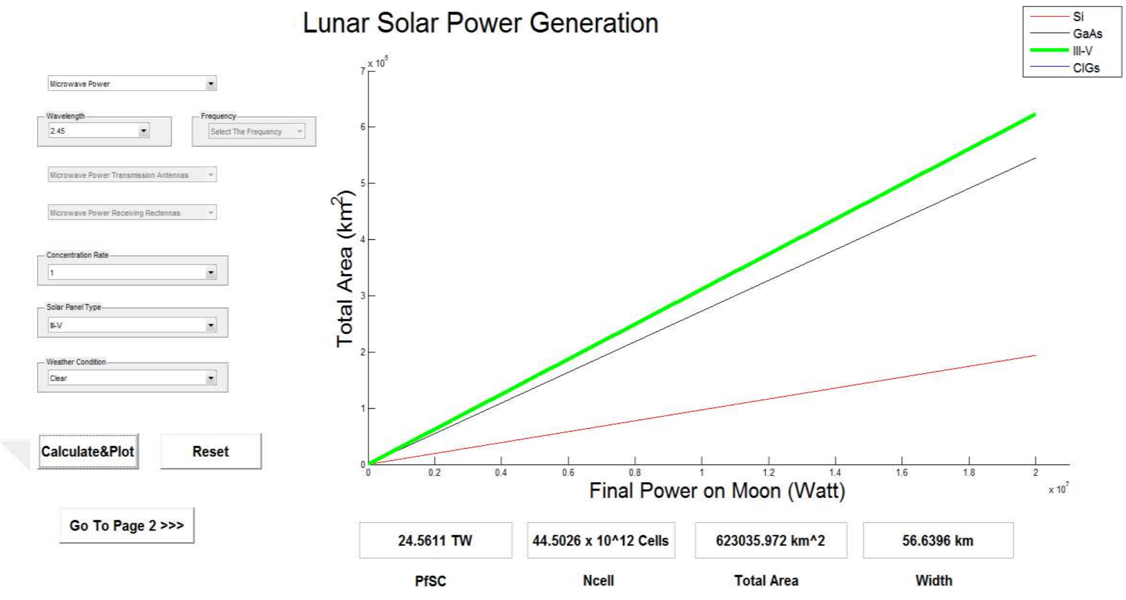


Figure 4.6 MPT, λ = 2,45 GHZ^{-1}, MultiJunction , Clear, No concentration

7) Selected; Multijunction Group III - V, heavy fog , concentration rate 3 , laser transmission, λ = 1,06 nm.

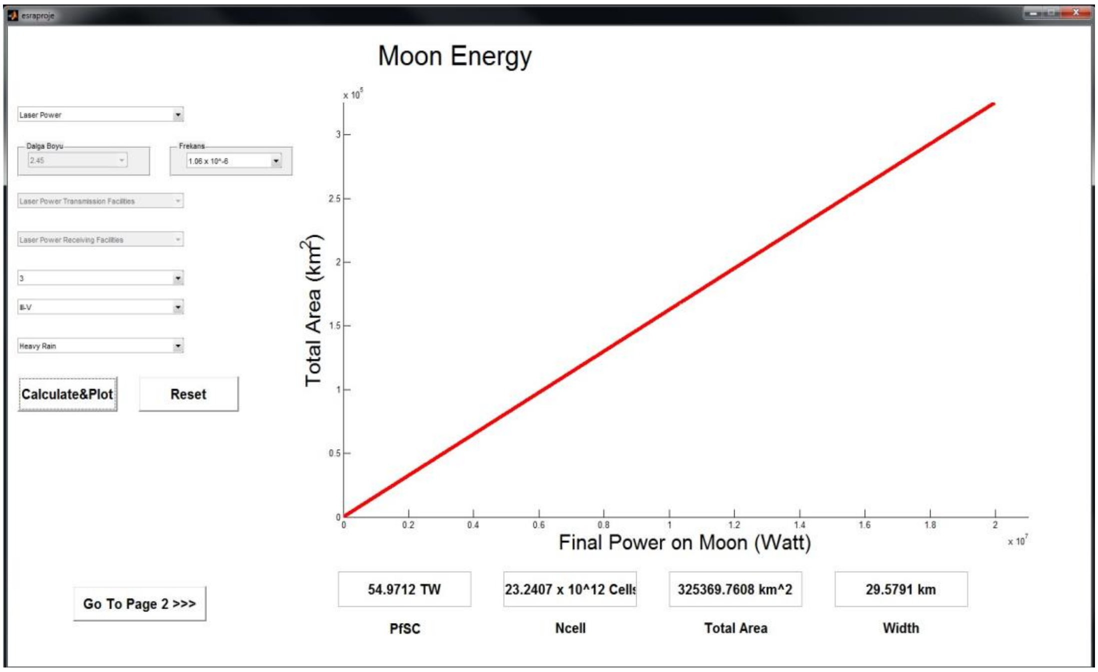


Figure 4.7 Average Power of Concentrated Multi-junction Cells vs Area on Moon

4.2. ANTENNA CALCULATIONS

1) Antenna Calculation Selected ; λ = 2,45 GHZ^{-1}, clear weather, Gaziantep, Beam intensity = 100 W / m^2.

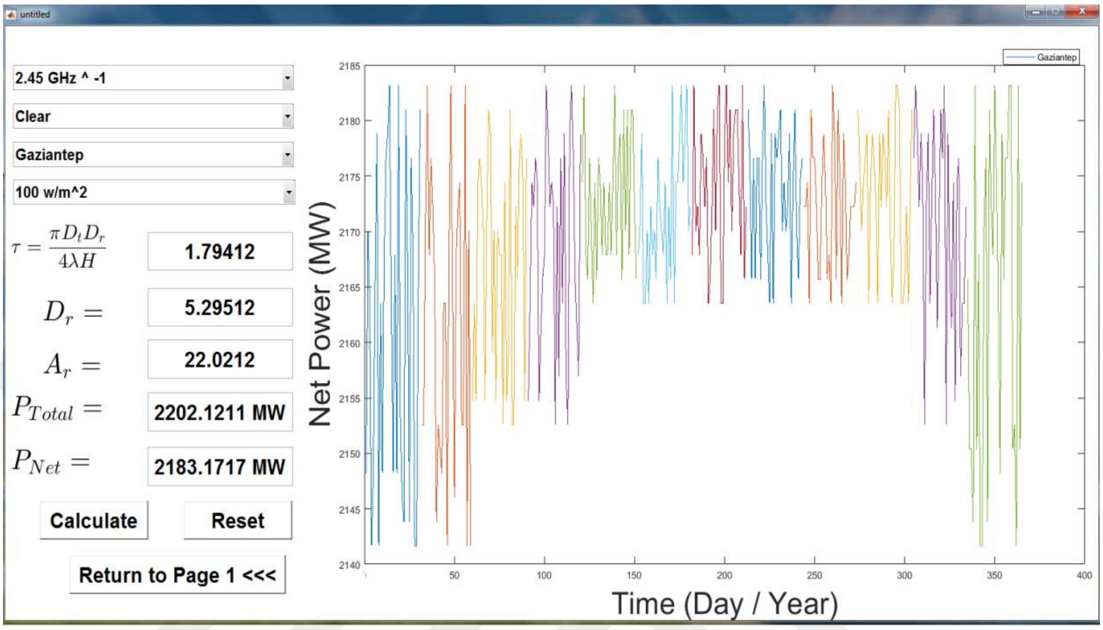


Figure 4.8 λ = 2,45 GHZ^{-1} , Clear, Gaziantep, 100 W/m^2

2) Antenna Calculation Selected ; λ = 2,45 GHZ^{-1}, clear weather, Gaziantep, Beam intensity = 230 W / m^2.

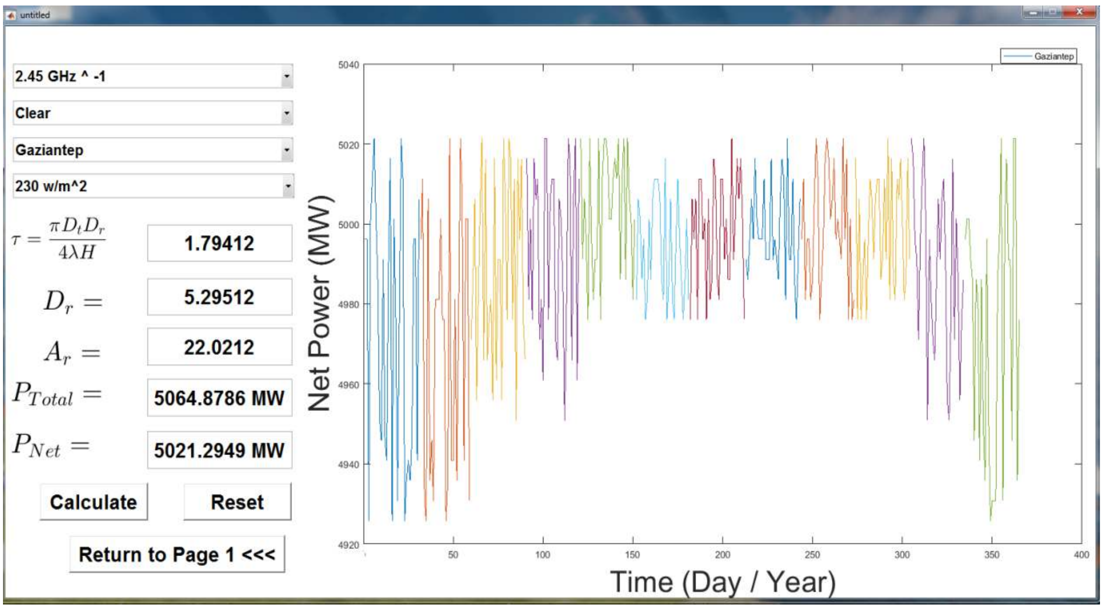


Figure 4.9 λ = 2,45 GHZ^{-1} , Clear, Gaziantep, 230 W/m^2

3) Antenna Calculation Selected ; λ = 5,8 GHZ^{-1}, clear weather, Konya, Beam intensity = 230 W / m^2.

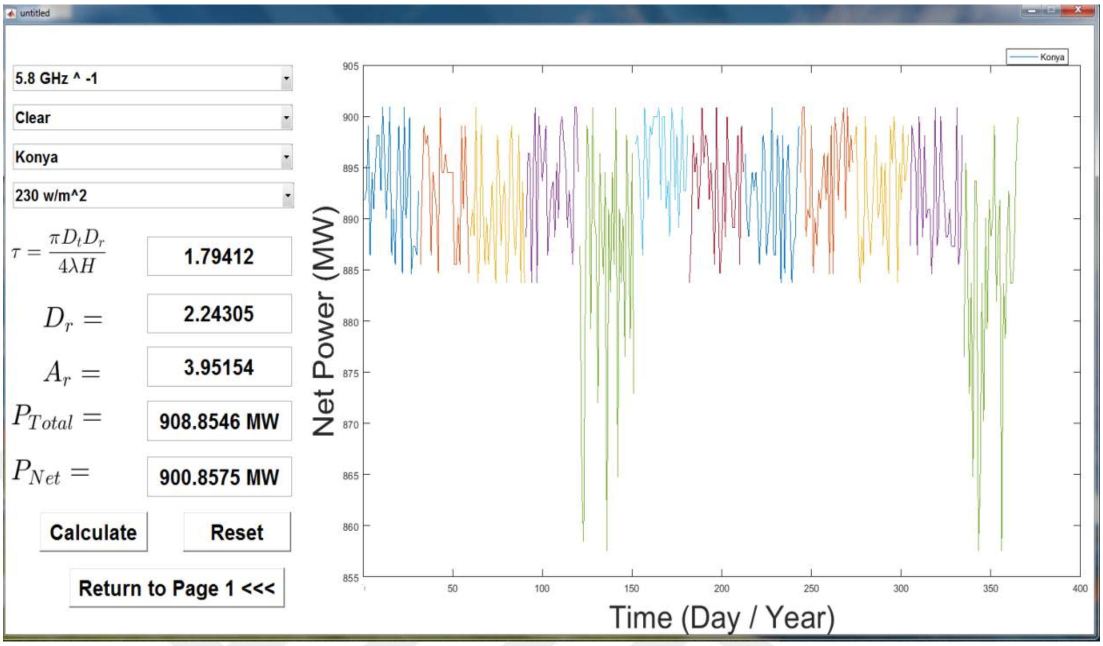


Figure 4.10 λ = 5,8 GHZ^{-1} , Clear, Konya, 230 W/m^2

4) Antenna Calculation Selected ; λ = 5,8 GHZ^{-1}, clear weather, Ankara, Beam intensity = 230 W / m^2.

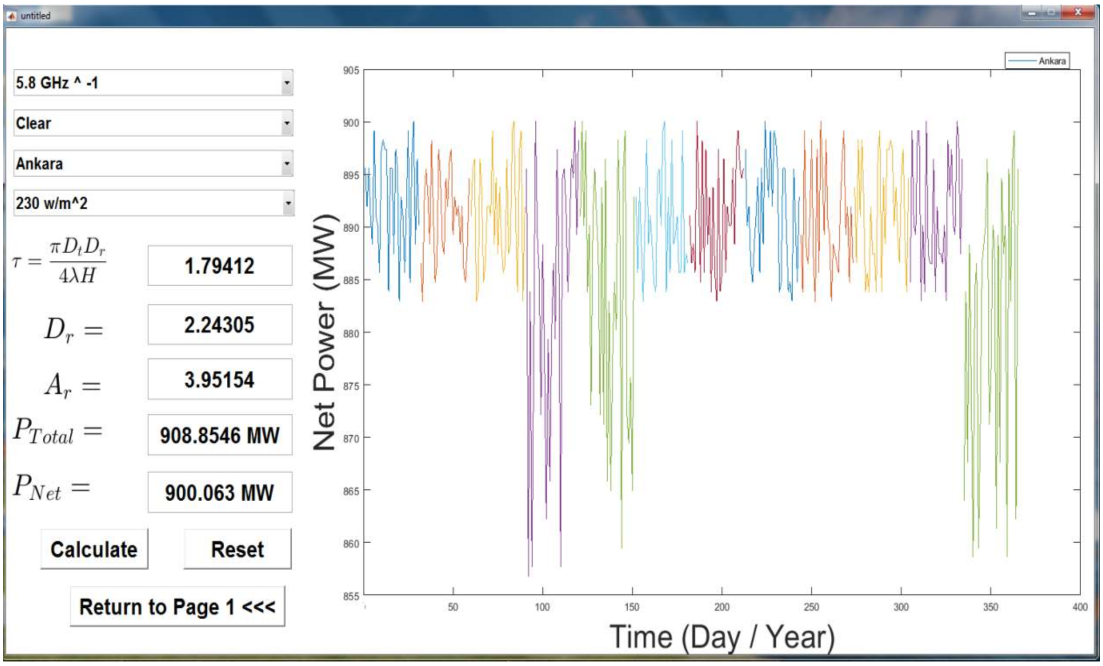


Figure 4.11 λ = 5,8 GHZ^{-1} , Clear, Ankara, 230 W/m

CHAPTER 5

DISCUSSION

5.1 ANALYSIS OF COMPUTATIONAL RESULTS

It is seen from the computational results in Figure 4.1 and Figure 4.2 that silicon solar cells have a good efficiency in lunar environment with or without concentration and cooling system. On the other hand, GaAs has a lower efficiency with or without concentration systems than Si cells on Moon conditions and the number of cell increases with respect to this total area increases. So, it can be concluded that solar concentrated systems have a big role in lunar solar power systems and even small efficiency changes of the solar cells affect the system too much. CIGS has the higest efficiency with a cooling system althoug it does not work under Moon conditions without a cooling system. But manufacturing CIGS from lunar materials is not discussed in previous studies so it is more logical to use silicon solar cells in lunar solar power systems. Assuming 2020s operating technology, all demonstrated by advanced systems as of today, reduces the area occupied by the LSP System to 0.16% of the lunar surface [3] The surface area of the Moon is 37,9 x 10^6 km^2 and 4,32 x 10^4 km^2 is the 0,113 % of the total Moon surface area. There is a small difference between our results and Dr. Criswell's calculations. The main reason of this is that Silicon solar efficiency is taken as 40 % in our calculations while he assumes it as % 35.As shown in Figure 4.8 and Figure 4.9, frequency selection is directly changes the area of the receiver antenna. There is a huge difference between the receiver antenna areas for λ = 2,45 GHZ^{-1} and λ = 5,8 GHZ^{-1}. Unfortunately, one of the most expensive part of a LSP system is the building receiver centers receiver antenna and on Earth [3], because of economic reasons, λ = 5,8 GHZ^{-1} may be a better solution for LSP system.

A rectenna can begin outputting commercial power after it reaches ~ 0.5 km diameter. One square kilometer area of rectenna area can output 180 MWe [24]. In our computational calculation with the assumptions efficiency = 0,96, λ = 5,8 GHZ, clear weather, D_T = 20 km, and beam intensity = 100 W / m^2, we need a rectenna that has a 2,245 km diameter and in this case we can get 395,154 MWe power in Gaziantep. In this case, the resulted power from the calculations is bigger than the twice of 180 MWe. On the other hand, as mentioned in Chapter 2, site potential analysis for rectenna construction in Gaziantep is not enough, more detailed and comprehensive studies can show better alternatives than Gaziantep for Turkey. When we compare the results with MPT and laser technology under the same conditions, we see that the efficiency of laser technology is lower than MPT. The computational program is in compliance with theoretical information. Of course, both systems have advantages and disadvantages but MPT is more popular than laser technology because of the concerns about laser beaming. It is necessary to consider all aspects of the health and safety of using microwaves or laser as the major method of delivering power to Earth. Finally, construction of the laser receiver facility in Mediterranean in borders of Turkey's sea should be a better option than the Black sea or Aegean in the perspective of distribution of the energy. But of course, site selection must be done more professionally. Security, military, politics and technical issues must be put into consideration.

5.2 ECONOMIC VIABILITY OF LSP SYSTEMS

There are two main economical question about lunar power systems. First question is; how to finance it? Uses of the Moon as a commercial power supply takes the interest of entrepreneurs all over the world, but still, their effort is not enough to develop a lunar base program in the near future. High cost of the system definitely requires public support and funding, also agency involvements in the project can play a role to overcome the economic problems [28]. The second important question about LSP system is the; economical potential of it. It would be better to fallow a step – by- step approach while installing a lunar base to eliminate the risks and unknowns before starting a gigantic project. By the way, public opinions and altitudes of the politicians about LSP will strongly affect the funding support. First defining the political dimensions and taking the public majority will be important. The cost assumption of Criswell's for 20 TWe LSP system is approximately around 1,75 T $. Reducing this cost is highly depend on the technological developments in the next years. After solving all the financial problems and taking the government and public support, political and legal feasibility of the system should be discussed.

5.3 POLITICAL AND LEGAL FEASIBILTY

Since, lunar solar power systems will be installed and operated in outer space, use the radio frequencies for the transfer and lunar materials for the construction on Moon, they will be subjected to the principles of space law and firstly to the freedom of outer space principle. According to the Outer Space Treaty [31], Article II: "Outer space, including the moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means". So, this law excludes all possibilities about national appropriation of any element of outer space. Secondly, using radio frequencies both for telecommunication in space and energy transfer to the Earth is another legal important issue. As mentioned in chapter 2, there are some instructions about power beaming to the Earth because of the effects on human health. First of all, safety issues must take into consideration during beaming and all possible damages must be calculated. In the case of delinquency, unwanted results may occur. There is definitely need for extensive testing and technology risk mitigation. If laser technology used for LSP can be considered as weapons, they can definitely not be assimilated to a weapon of mass destruction. Frequency selection for the LSP telecommunication systems is an easy manner than the energy transmission. Allocated frequencies by International Telecommunication Union (ITU) for the purpose of industrial, scientific and medical applications may be used.

Even there are many risks and uncertainties about LSP systems, many nations understand their growing energy insecurity with respect to limited fossil fuels, conventional fission nuclear power, and terrestrial renewable energy sources. For this reason, they are looking seriously at space solar power but it is as fact that such a big plan needs cooperation between the countries. At this point, new questions appear, this cooperation may affect both political and economic balances on the World [16].

CHAPTER 6

CONCLUSION

In the light of mathematical and computational calculations, LSP System has a huge potential of power to utilize as a commercial power on Earth. It eliminates all the undesirable characteristics of the current energy systems. Up to now, LSP is the biggest solar power project that is reliable, safe and clean so it is an encouraging idea that can be alternative to all other small scale options. Also, it eliminates the worries about day – night cycle and climate change unlike on Earth, it promises a 7 / 24 continuous power. If one compare the computational results for three location on Turkey in same conditions and for λ = 5,8 GHZ^{-1} , clear weather, beam intensity at the center of rectenna is 230 W/m^2 , the results for Gaziantep would be 901,033 MW, for Ankara it would be 900,063 MW and for Konya it would be 900,857 MW. The differences between the P_{net} energy values causes because of latitude effect and the annual weather conditions of the cities. We can conclude that the most important parameters of a LSP system are power transmission type, the selection of solar panel type, the efficiency of concentration systems and the beam intensity at the center of rectenna. The latitude effect and weather conditions on Earth can be negligible while transferring 20 TW of energy to Earth. On the other hand, a political strategy for the LSP is also very important, serious consideration should be given in many aspects related to the LSP construction and its full use. If the plan comes true, the Developing Nations can afford LSP electricity according to the Criswell's assumptions. LSP electricity may accelerate the economic growth of all nations because it gives changes to all nations to get energy independently from atmospheric effects, climate and location so, this situation may change all the power balances on the World. When putting all these concerns besides, statistical studies shows that soon or late we will need a long-lived and clean energy supply to meet growing energy demand of the World. In case of a more economical solution cannot find, expensive but reliable LSP or SPS system should be applied in near future.

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