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Energy Mules, a Novel Solar Power Satellite System Architecture Capable of Energy Storage

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Abstract

This project aims to tackle energy availability in situations where no alternative exists, using a new modular solar power satellite (SPS) system architecture. The goal is to supply power to locations with no direct solar incidence, such as the case of lunar bases during the body's night, by researching three main fields: solar power generation, energy storage and wireless power transfer. Each module of the SPS consists of a tile that generates power through a solar concentrator coupled to photovoltaic cells. The resulting DC electric power is stored in a battery pack, allowing non-stationary orbits to collect energy in sunlight and deliver it when flying over ground energy collectors. This way, it is possible to continuously supply power to moon stations, which will be delivered wirelessly via microwaves: DC-RF converters will be used to feed phased antenna arrays that emit beams. Electromagnetic lenses will be used to focus the beam, optimizing its shape for low divergence propagation and reducing the overall spillover losses. This analysis will be performed via the quasi-optics framework. Each tile will be self-sufficient but will have a simple bus connection on each side, enabling coupling to nearby tiles. The overall structure can be as large as needed to supply the necessary power levels. This large SPS array should have a central control unit for implementing algorithms to create a focus of energy in the form of a directive beam and a feedback channel pilot to optimize the beam focus direction. This modular approach will enable the repairing, replacing or upgrading of the overall SPS system, one tile at a time, to keep it functioning and updated to the ever-changing needs of power supply in celestial bodies. This will significantly reduce the system's impact on the climate by reducing resource exploration, allowing maintenance tile by tile rather than the overall structure. Finally, we aim to present a near-term demonstration of a smaller set-up on Earth to validate the concept we are developing. A general discussion will also be made on how this SPS project can mitigate climate change issues, mainly due to our modular and quasioptical approach, which enables a significantly reduced overall system compared to other approaches.

Keywords: solar power satellite, energy source, wireless power transfer, quasioptics, battery, energy generation

Nomenclature

e	Euler's number
η	Efficiency
λ	Wavelength
ϖ_0	Gaussian beam waist
ϖ	Gaussian beam radius
z_c	Confocal distance
L	Wireless power transfer distance
m_{tile}	Mass of each tile
a_{tile}	Side of each hexagonal tile
N	Number of tiles
A_{total}	Total area of the SPS
e_{orbit}	Orbits' eccentricity
a	Orbital semi-major axis
T	Orbital period

Acronyms/Abbreviations

DAC	Digital to Analog Converter
DC	Direct Current
EM	Electromagnetism
LDS	Luminescent Down-Shifting
LEO	Low Earth Orbit
LRO	Lunar Reconnaissance Orbiter
PMU	Power Management Unit
PV	Photovoltaic
RF	Radio Frequency
QO	Quasioptics
SPS	Solar Power Satellite
WPT	Wireless Power Transfer

1. Introduction

The question of energy generation and distribution is crucial to our modern society, which relies evermore on electrical technologies. Alternative energy sources are now viable, which aim to offset the disadvantages of fossil fuels, but have limitations of their own.

Of these, solar power is one of the most promising: electrical power is generated through a static and relatively compact device that needs little maintenance. However, it only works when there is sufficient sunlight, which prevents their usage throughout the night. Furthermore, the atmosphere limits the amount of power arriving at the solar cells, reducing the overall efficiency and energy produced.

To overcome these issues, the Solar Power Satellite (SPS) system has been proposed. This concept is composed of two main subsystems, that of solar power generation and wireless power transfer: electrical energy would be generated by a satellite constellation in orbit of a celestial body, where higher solar generation efficiencies could be achieved due to the lack of atmosphere. That power would simultaneously be transmitted to the intended target via microwaves, resulting in a green energy source that is constantly available. First proposed by Peter Glaser in 1968 [1], the SPS project was advanced by DOE/NASA studies [2] throughout the 1970's. Since then, various types of SPS concepts have been proposed, with numerous projects being developed worldwide [3, 4, 5].

The SPS concept was inspired by the work of William Brown, on microwave wireless power transfer (WPT). Most of the SPS models use microwaves because the power conversion efficiency, both at the transmitter and receiver, and the transmissivity through the atmosphere is generally higher for microwaves when compared with lasers. [6]. To achieve high transfer efficiency, the electromagnetic (EM) radiation can be focused into a beam and directed towards intended targets [7, 8, 9, 10]. It was in the context of this research that the SPS was proposed, prompting further development into WPT. A NASA/DOE investment enabled two important experiments that still hold WPT records: one for the maximum DC-DC efficiency of 54% [11], and the other for the highest outputted DC power of 30.4 kW for an impressive distance of 1540 m (1 mile) [12].

These results inspired various nations to start their own SPS endeavors, especially Japan, whose first study was an experiment in space. Sent by a rocket, the high-altitude set-up aimed to study the effect of microwaves through the higher layers of the atmosphere for understanding the behavior of a beam propagating from space down to Earth [9, 13, 14].

Among many other novel ideas, the Japanese also proposed the first modular and integrated SPS constellation in 2000. The SPRITZ project consisted in an assembly of a solar power cell connected to a DC-RF converter and microwave antenna. These integrated tiles could be connected to other modules in space and increased as needed. Recently, the U.S. also proposed a similar "sandwiched" approach in the SPS-ALPHA [15].

However, some issues regarding SPS remain to be solved: even in orbit, satellites pass through zones in which they are obscured by the Earth's shadow and no power is generated. Additionally, satellites orbiting the Earth travel at such high altitudes that a power transfer beam will suffer large divergence resulting in a wide receiving area, spanning kilometers. Furthermore, the issues regarding the safety of humans and wildlife as well as the logistics of airplane travels, need to be considered.

The main novelty of the present work is the proposal of a compelling SPS that deals with these issues. The main goal is to supply power to a lunar base, which comes at an opportune time, when the space agencies are planning to return to the Moon and build a permanent base [16]. With this celestial body, most of the problems are not even an issue: there is no atmosphere on the Moon, nor is there any life to be protected. However, the most important is that the altitude of the SPS can be significantly reduced, resulting in a receiver area of meters.

To achieve this, this novel architecture proposes two main contributions to SPS architectures: adding another subsystem, that of energy storage and implementing quasioptics for increasing the WPT efficiency by focusing microwaves. The former will provide flexibility to the system, enabling power supply even during the night and will be implemented through commercially available battery packs. On the other hand, the latter reduces the overall system size and energy losses in the beam. As far as the authors are aware, none of these have been proposed in SPS projects before. These are the main novelties of this work.

Other original contributions increase the solar power generation efficiency, deal with power management unit and the microwave transmitter. The former is obtained by using materials that downshift solar energy into the region that is absorbable by photovoltaic (PV) cells [17].

Regarding the WPT, the beam divergence is still a considerable problem. This project is based on previous work that implementation the quasioptical (QO) framework [18] to understand and control microwave beams and the way they propagate, for maximizing the beam efficiency. This theory adapts the tools of optics to contexts with high divergence and can be used to study microwaves traveling distances of meters and kilometers.

As far as the authors are aware, previous to the work of this group, QO has been proposed for some components of WPT but not used for complete system analysis, as is the case here. The main reason being that

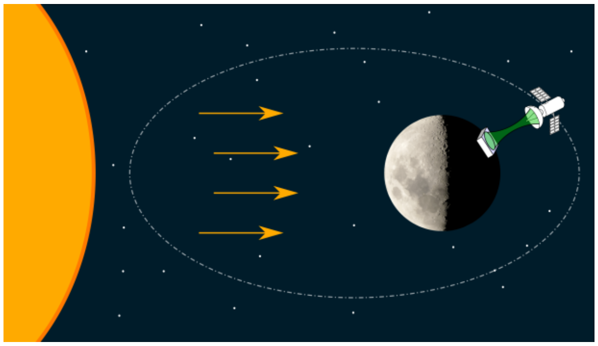


Fig. 1 – Illustration of the proposed solar power satellite architecture orbiting the Moon.

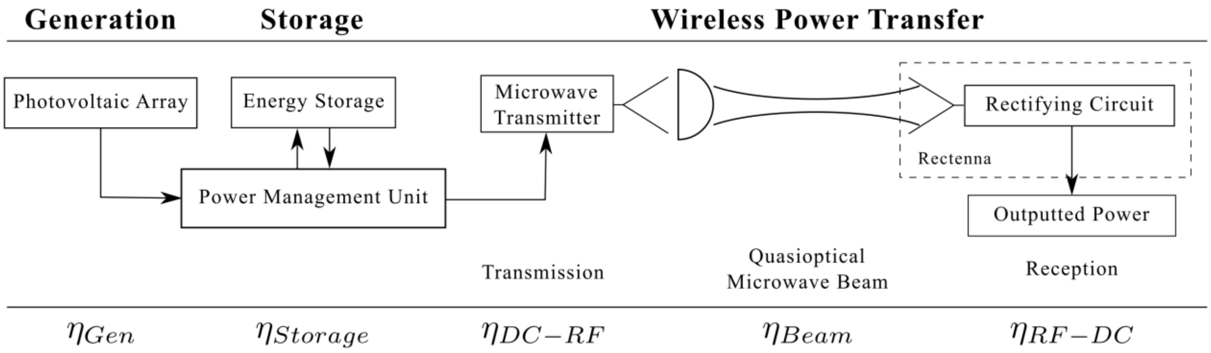


Fig. 2 - Schematic of the overall system representing the energy flow from generation to reception. All the major subsystems are detailed: solar power generation, energy storage and wireless power transfer.

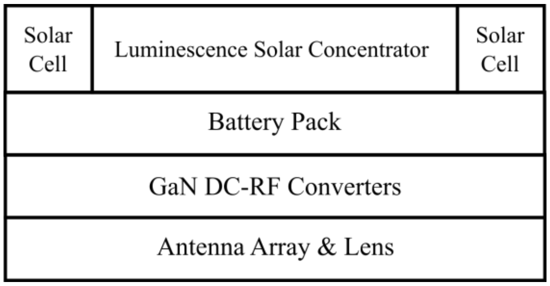


Fig. 3 - Representation of a single module, containing all major subsystems.

antenna theory was the main framework for WPT, due to the engineers' background in electrical engineering. This group has implemented QO as the fundamental theory for WPT and has developed antennas and focusing components for achieving higher beam efficiencies, from reflectors [19, 20] to lenses [21, 22].

This paper begins by explaining the overall goal and components of the proposed solution. In the following section, each subsystem is specified and explored in depth. Finally, an analysis is presented regarding the usage of this architecture with a discussion on demonstrators that aim to validate this solution.

2. System Overview

In general terms, the SPS architecture presented here is composed of the traditional subsystems, solar power generation and wireless power transfer, while adding another one, that of energy storage. This grants higher flexibility to the solution: as represented in Fig. 1, it will be possible to generate energy when the satellite is sunlit and store it in batteries. After travelling to the closest distance to the target on the surface of a celestial body, the system can transfer the stored energy wirelessly. In this way, power can be supplied even if no sunlight is incident. The addition of energy storage is a novel concept in SPS. It will enable applying SPS to multiple new scenarios and space missions, but also brings some challenges with most significant being the increased weight per module. Nevertheless, the advantages of this approach enable providing energy to

Figure 2 represents the energy flow of our system: a power management unit (PMU) will store the power generated by the photovoltaic (PV) stored into batteries. This will later be used to feed DC-RF converters for generating microwave oscillation, which will in turn feed antennas that radiate a specific microwave beam. Lenses will be used for transforming the beam and creating focus of energy which minimizes the spillover losses and the overall beam radius. The lenses will also direct the beam towards the receiver on the lunar surface. Finally, the receiver consists of an assembly of rectenna elements, which are antennas coupled to rectifying circuits [23], that will finally output DC power for the most varied needs.

The shortest distance between the satellite and the target is crucial for defining the actual parameter values because it will define the width of the microwave beam used for wireless power transfer. The shorter the distance, the narrower will the beam be and, consequently, the antenna and lens components. This distance is dependent on the orbit chosen for the satellite constellation and will coincide with the satellite altitude at the orbit's periapsis.

2.1 Orbital Considerations

Contrarily to the Earth, the Moon contains mass concentrations due to comet impacts, which contribute to an irregular gravitational field. These result in perturbations to satellites' dynamics orbiting the Moon, especially at low altitudes, having resulted in the loss of previous missions [24]. Over the years, specific orbital parameters have been discovered which enable stable and indefinite orbits, which are called "frozen" orbits [25].

The satellite that was used as reference for the present study was the Lunar Reconnaissance Orbiter (LRO) from NASA, whose elliptical orbit around the Moon has one of the shortest periapsis, of approximately 20 km [26]. Fig. 1 represents the novel SPS in the LRO orbit.

A model of our system was designed and simulated in a script, travelling in LRO's orbit, to discover how

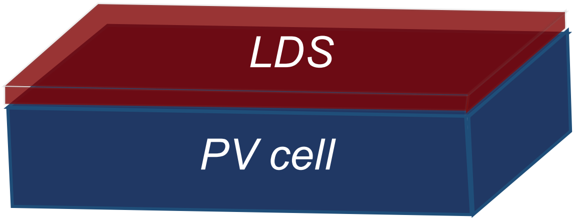


Fig. 4 - Luminescent downshifting photovoltaic cell approach representation.

much energy can be stored per orbit, how far the satellite is from the lunar surface, at all times, etc. This enabled us to understand multiple system details, such as the influence of the temperature variation on the solar panel's efficiency. In this specific type of orbit the satellite passes close to both Moon's poles on each revolution, due to an inclination between 60 to 90 deg., with a period of around two hours. As the goal is to provide power to a station when the Sun's energy is not sufficient, this study was made to identify how long the satellite stays in the dark, paying attention to both shadow regions: umbra and penumbra [27].

Alternatively to the solution with batteries, a relay system could be used for transmitting power. However, the low efficiency of the wireless power transfer links limits the amount of power that can be supplied to the station, to the point where it is not viable. Instead, one can increase the number of tiles in each satellite assembly for higher energy generation and transfer, or add multiple constellations, so that the delay of power supply is reduced and the overall energy is increased.

Finally, environmental awareness is imperative, not only concerning the Earth, but also regarding the Moon and modularity of this project guarantees a highly sustainable solution. This is because each module can be repaired or even replaced, individually, without affecting the remaining system elements.

Further discussion about sustainability will be presented in the result section.

3. Description of the Subsystems

A detailed discussion of the proposed SPS solution will be presented now, following each component present in a module, in the order of energy flow. As represented in Fig. 3, all modules will contribute to the energy generation, storage and wireless power transfer.

3.1 Spectral conversion devices

The mismatch between the photovoltaic (PV) cells absorption and the solar irradiance is one of the major limitations towards more efficient PV energy conversion [28]. Luminescent down-shifting (LDS) layers are coatings directly applied on the PV cell surface, as represented in Fig. 4, which absorbs the incident radiation complementary to that of the PV cell and, subsequently, re-emit, with a compatible wavelength, towards the PV cell. They can, thus, be seen as additive devices able to enhance PV cells performance under typical operation conditions.

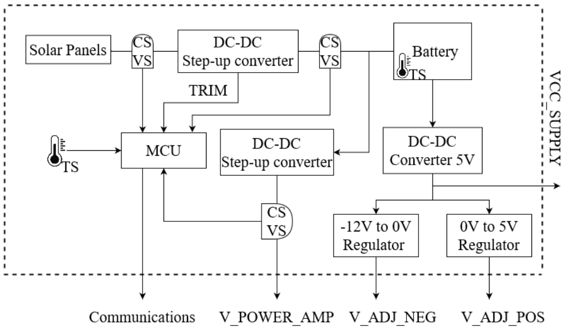


Fig. 5 - Block diagram of the power management subsystem.

Over the years, LDS materials based on organic fluorescent molecules such as quantum dots, [29] organic dyes, [30] and lanthanide ($Ln^{3+} = Eu^{3+}$, Tb^{3+}) [31-33] complexes incorporated into polymer [32] or organic-inorganic hybrid materials [17] have been widely proposed to be used as LDS layers on PV cells. This approach has been proven effective for c-Si PV cells under the global standard AM1.5G of solar radiation, by yielding 9% electrical power relative increase and a ~23% absolute increase in the external quantum efficiency in the UV spectral region [17].

The size of the chosen solar panels is 160x138 mm and the estimated conversion efficiency nears 25%.

3.2 Energy storage

The power generated will be stored in space-grade battery packs. The block diagram of the developed power management unit is illustrated in Fig. 5.

The solar panels will be connected to an i7C4W008A120V-0F1-R boost converter, whose trim will be done via DAC, through the system's microcontroller. The output of the boost converter will be connected to another converter, the i7A4W033A033V-

Table 1 - Power management unit outputs.

Output	Voltage & Current
V_POWER_AMP	22V @ 15A
VCC_SUPPLY	5V @ 2.5A
V_ADJ_POS	[-5; 0] V (I < 50mA)
V_ADJ_NEG	[0; 12] V (I < 50mA)

Table 2 - Electrical characteristics of the 4S1P VES14 battery.

Nameplate capacity	4.5 Ah
Battery voltage range	13.2 V to 16.4 V
Nominal energy	64 Wh

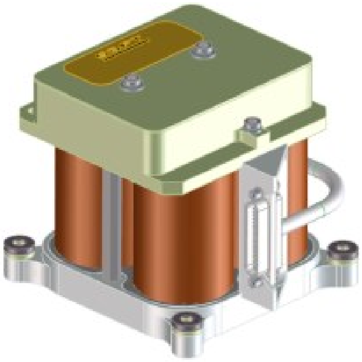


Fig. 6 - Representation of a 4S1P VES14 battery, as obtained from [34].

0C1-R (buck type), whose output will be connected to a power amplifier (V_POWER_AMP) and to the system battery.

The energy stored by the battery will be connected to another converter, the PDQE15-Q48-S5-D, which must have a voltage of 5 V at the output (VCC_SUPPLY), which must be regulators, one inverter [-12; 0] V and the other is non-Inverter [0; 5] V.

Some current and voltage sensors will be used to know if the panels are sunlit or not.

It is also important to control the temperature of the system, particularly of the battery. For this effect, some temperature sensors will be used.

The power management unit outputs are presented in Table 1.

A generic search was done in order to choose a battery already approved in the spacecraft market in order to ensure as much reliability as possible in this project.

So the energy storage element used is the 4S1P VES14 battery, depicted in Fig. 6. This battery was designed for LEO (Low Earth Orbit) satellites with a life duration up to 12 years.

In such way, the electrical characteristics of this battery are presented in Table 2.

3.3 Transmitter

When it is time for wireless power transfer, the energy stored in the batteries will be used for generating microwaves. Therefore, it is necessary to convert the DC energy into RF, which is done by the transmitter.

The WPT transmitter architecture is shown in Fig. 7 and is composed by 4 independent channels that should provide a total power of 40W. The DC power required to operate all the active devices is provided by the solar panels together with the energy storage electronics.

To generate the RF signal is used a VCO from Analog Devices HMC739LP4 was chosen, with a frequency range from 23.8 to 28 GHz and an output power of 8 dBm. After this stage a Band-pass filter from Mini-circuits BFCQ-2802+ that operates from 27.5 to 29.5 GHz is used to remove the harmonics generated by the VCO. Then the signal is amplified by a driver from Analog Devices HMC863ALC4 with a frequency range from 24 to 29.5 GHz and presents 24 dB of gain and 0.5W of output power.

That signal is then split into 4 equal signals that will follow an amplification chain (Gain Block + Driver + PA) resulting in a total power of 10W per channel. The gain block presents 18 dB of gain and operates from 26.5 to 31 GHz and the PA provides 41 dBm of output power with 25% of efficiency. The power splitter is from Knowles and operates in the range from 24 to 32 GHz with 1 dB of excess insertion loss.

Another important point considered was the possibility of including custom phase shifters and variable attenuators in each channel in order to correct the possible differences between channels. This question hold be further studied after the test and validation of the different elements of the transmission chain.

The required power to operate the system's transmitter is 215 W, regarding the components specifications.

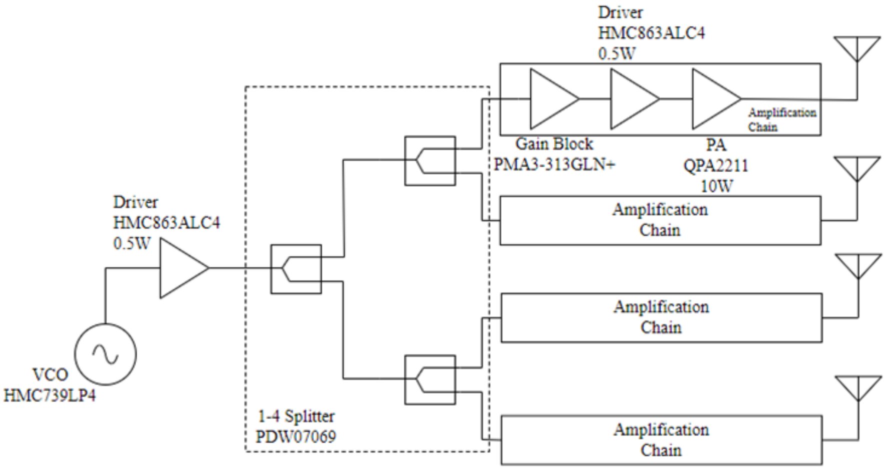
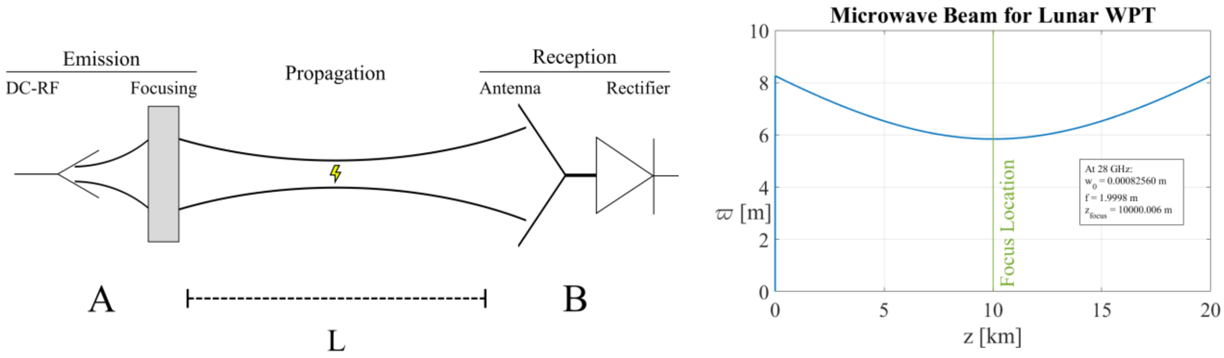
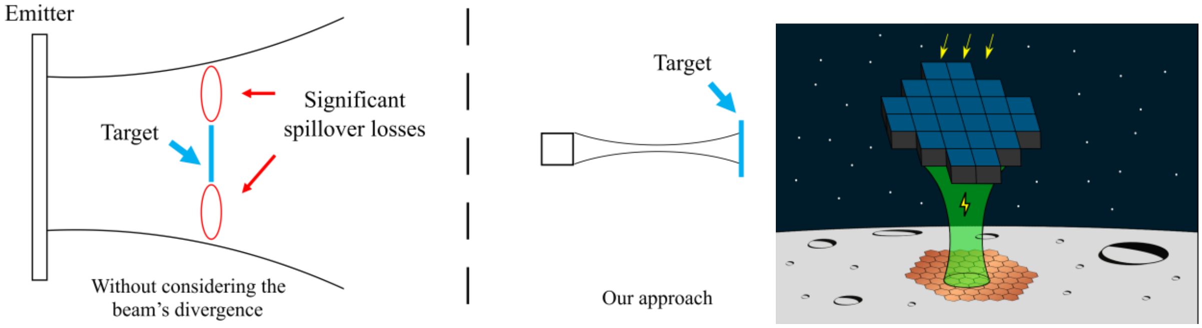


Fig. 7 – Wireless power transfer transmitter architecture.



a) b)

Fig. 8 – Details of the radiative part for transferring power wirelessly to a receiver on the lunar surface: (a) schematic of the quasioptical system. (b) representation of the beam radius throughout the transfer distance. The focus is located at 10 km, exactly half the distance between the SPS and the lunar base. The maximum beam radius is 8.256 m, significantly more compact than traditional SPS systems.



a) b)

Fig. 9 – (a) Comparison between a system that does not use the quasioptical approach to focus energy and one that does. (b) Illustration of the well contained microwave beam, transferring power from the satellite to the receiver on the lunar surface with no spillover losses.

3.4 Wireless Power Transfer

One of the most crucial parts of SPS systems is the wireless power transfer. A schematic of the overall radiative WPT subsystem is shown in Fig. 8-a), where it is considered that the goal is to transfer power from point A to point B, with A being the satellite and B the lunar surface. Hence, in the emission, antennas will radiate microwave beams that will be focused by lenses. This optimized beam will travel the *power transfer distance*, L, with minimum loss, and be received in point B by a rectenna.

WPT has traditionally been one of the most lossy components of SPS projects. To solve this issue, the quasioptical approach is implemented here to focus microwave beams, reducing spillover losses and increasing the overall beam efficiency. Quasioptics is a theoretical framework used for analyzing EM radiation. It is based on optics but is updated to include the beam's divergence. In this sense, the radiation is no longer represented by thin rays, but by gaussian beams [18]. The radial distance at which the power density falls to $1/e$ of the on-axis value, where e is the Euler's number, is the *beam radius*, ϖ. Assuming a propagation in the $\hat{z}$ direction, z_0 is the point at which the power is most concentrated and the beam radius achieves its minimum value, called the *beam waist*, ϖ_0.

With ϖ_0 and z_0, the beam radius at any distance from the waist, z, is given by: $\varpi = \varpi_0[1 + (z/z_c)^2]^{(1/2)}$, where, $z_c = \pi\varpi_0^2/\lambda$ is the *confocal distance*, a parameter which details the distance from z_0 where the beam remains collimated, presenting minimum divergence.

Through QO, the beam transferred between the SPS and the lunar base can be optimized: for a fixed distance, the beam radius can be reduced by increasing the frequency of operation. Hence, for the distance of around 20 km, which is the point of lowest altitude of the chosen orbit (periapsis), the frequency of 28 GHz was deemed adequate. Then, a beam was designed for WPT, whose representation is visible in Fig. 8-b).

Now arises the question of how to generate this beam: arrays of horn or patch antennas will generate microwaves that will be focused by lenses into the required beam.

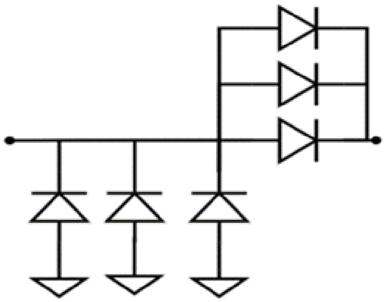


Fig. 10 - RF-DC converter's rectifier design with six diodes.

As represented in Fig. 9-a), this approach enables a much more compact solution: higher levels of efficiency are achieved, transferring more power to the intended target, since the spillover losses are negligible. As such, less power generation is needed than in traditional SPS systems.

On the other hand, the system is more complex due to the implementation of lenses. Their positioning and alignment are crucial for creating the optimal beam and assuring it is directed towards the target.

3.5 Receiver

The receiving part has also been studied, especially for the laboratorial demonstrators.

The RF-DC converter should be designed for an input power of 30 dBm and a frequency of 28 GHz. The chosen Schottky diode for this project was the MACOM MA4E1317, whose maximum input power is 20 dBm, and its operating frequency can go up to 80 GHz. As the chosen diode only endures a power of 20 dBm, the rectifier topology should ensure that the diode does not break. For this reason, the topology used is in Fig. 10.

Using the rectifier configuration of Fig. 10 to design an RF-DC converter and equation (1):

$$\eta\,(\%) = \frac{P_{DCout}}{P_{in}} = \frac{\frac{v_{out}^2}{R_{load}}}{P_{in}} \tag{1}$$

to compute the RF-DC efficiency. The designed converter has an efficiency of 30% at 30 dBm and an output voltage of 7V, as it is possible to observe in Fig. 11-a) and Fig. 11-b), respectively.

The RF-DC converter schematic and a real photo of the final PCB after manufacturing are presented in Fig. 12 and Fig. 13, respectively. The proposed device is important because when incorporating the overall system, in the receiver side it becomes possible to measure the received power in order to evaluate the system's efficiency.

Table 3 – Physical and orbital system parameters.

Symbol	Terminology	Value
m_{tile}	Mass of each tile	10 kg
a_{tile}	Side of each hexagonal tile	22 cm
N	Number of tiles	2611
A_{total}	Total area of the SPS	304 m^2
e_{orbit}	Orbits' eccentricity	0.04
a	Orbital semi-major axis	1826 Km
T	Orbital period	117 min

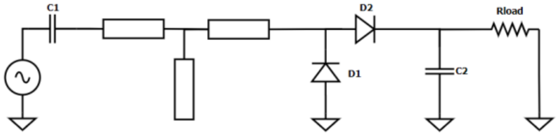


Fig. 12 - Schematic of the designed RF-DC

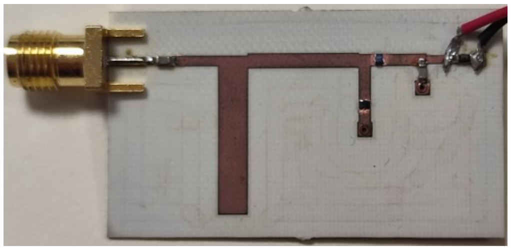
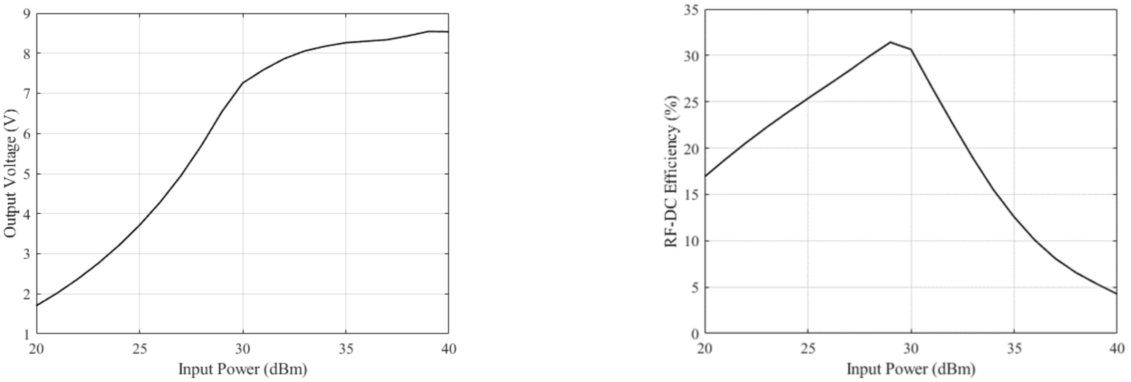
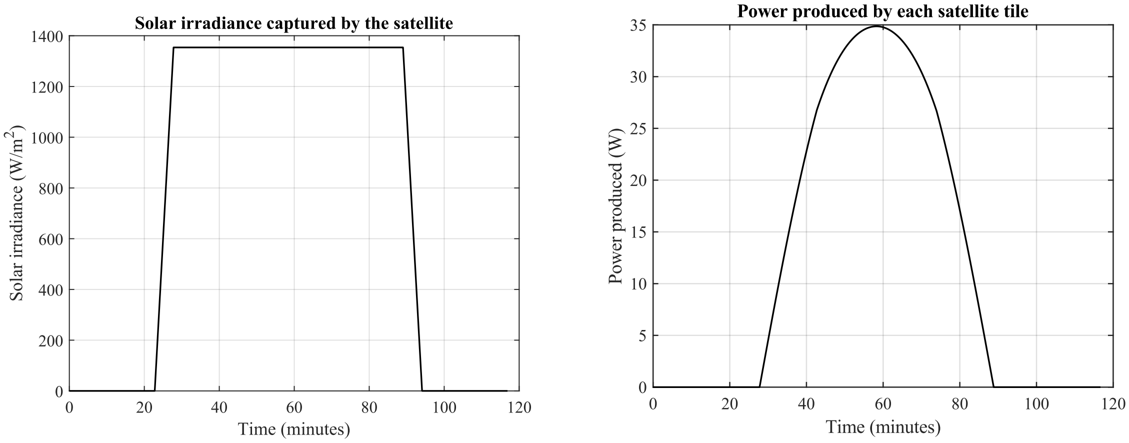


Fig. 13 - Manufactured PCB of the designed RF-DC converter.



a) b)

Fig. 11 – (a) Output voltage of the designed RF-DC converter. (b) Efficiency of the designed RF-DC converter.



a) b)

Fig. 14 - Estimation of solar irradiance arriving at the satellite over one revolution around the Moon (a) and power generated by each satellite tile in one revolution (b).

4. Results

A description of actual results will now be presented.

4.1 Novel SPS Architecture

The first major result is the new SPS architecture, capable of energy storage. It significantly increases the possible applications of SPS systems in future space missions, since it can be adapted to various different scenarios. Any celestial body can be supplied with electrical power through this system, from asteroids, comets, moon and even Mars and the Earth, etc, with small adjustments.

As described previously, the satellite is composed of multiple hexagonal tiles, which are connected together (Fig. 3). According to the demonstrator that is being developed, each tile will have a hexagonal side of 22 cm, resulting in an area of 0.12 m^2 and according to the necessary beam size determined in the wireless power transfer section, this results in 2611 tiles.

Generally, the supplied power level can be increased by simply adding more modules, while different transfer distances will require changes in the frequency of operation and therefore all the WPT subsystem.

Finally, for missions that are further away from the Sun, the solar irradiance will be smaller. It may be necessary for the satellite to complete more than one orbit for generating sufficient power before transferring it, contributing to the systems' flexibility.

4.2 Modelling and simulation

As described in the system overview section, a script was developed for modelling and simulating the satellite orbiting the Moon. Based on a similar previous work from this group [35], the real-time simulation implemented dynamic physics models, for calculating the position and orientation of the satellite. Information regarding the physical and orbital parameters can be found in Table 3. Through the simulation, it was concluded that the satellite's orbit has a period of 117 min, 46 min of which are in complete darkness in the Moon's umbra, about 10 min in penumbra and the remaining 61 min under direct sunlight.

This information was used to extract other parameter values:

- The solar irradiance that the satellite is subject to, which varies with whether the satellite is in the Moon's umbra, penumbra or neither.
- From the satellite's position, the angle that the solar panels make to the sun's direction will affect how much power is generated. A sinusoidal function was assumed.
- The satellite temperature, which will affect the battery's performance. This was based on the LRO's satellite [36].
- Finally, the time during which the satellite has line-of-sight with the lunar base is used for determining the amount of time during which wireless power transfer is possible.

All this information is used to estimate the total energy produced and stored by the satellite in one orbit, as well as the energy that is supplied to the lunar base.

4.3 Power Budget

The satellite simulation enabled the analysis of the complete electrical power and energy, from generation to supply, which will be discussed in this section.

4.3.1 Power generation

Firstly, the power generated depends on two quantities: the solar irradiance at the solar panels, and solar panels conversion efficiency.

Table 4 - Power considerations per orbit.

	Per tile (W)	Total system (kW)
Peak Power generated	35	91.4
Beam power TX	40	104
Beam power RX	28	73.1

The former is the amount of solar power per square meter and can be considered the same for the Earth, Moon and orbiting satellite, due to a relatively small deviation in the distance to the Sun. Thus, the total solar irradiance value in the Moon surface and, consequently, on the satellite, when under direct sunlight is approximately 1354 W/m^2 [37]. On the other hand, this value is considered null when the satellite is in the umbra. During the intermediate region, the irradiance is considered to vary linearly from zero to the maximum value, as is represented in Fig. 14-a).

Regarding the solar panels, the dependance on the angle between the solar panels normal vector and the vector pointing to the sun, is due to the lack of attitude control mechanism in this project, typical of the modular approach. It is considered a disadvantage for the amount of energy generated, but an advantage in terms of manufacturing cost and sustainability. This effect has been implemented through a sinusoidal function.

To calculate the amount of power generated by the system taking into account the solar irradiance of the satellite, the area occupied by the chosen solar panels was determined. Since each tile is composed by 6 of these panels, the coverage area of the tile is 91% (0.11 m^2).

Finally, a solar panels' characteristic efficiency of 25% was used, as expected by the implementation of the downshifting layers discussed previously. The influence of the temperature was added, contributing to around 0.2% loss for each degree above 25 ºC.

4.3.2 Power management

Then, the energy variation associated to each SPS tile can be determined. The generated power is graphically represented in Fig. 14-b), resulting in the storage of 19 Wh of energy per tile in each revolution around the Moon for this orbit (about 2 hours). A power management efficiency of 80% is considered, which includes the charging and discharging of the batteries, as well as the feeding of the WPT transmitter.

In terms of energy consumption, it was assumed that 8 Wh per tile were necessary to keep the satellite operating normally per orbit, thus 11 Wh of energy are available for the transmission link.

4.3.3 Wireless power transfer

Since the transmitter system requires 215 W of power, this amount of stored energy enables transmission for 3 minutes. As described, the output of the transmitter is 40 W which still flows through the antenna and the lens where at least 70% efficiency is expected, before reaching the station on the Moon's surface. Then, 28 W of microwave beam power reaches the Moon. From the simulation, it was calculated that the line-of-sight between the SPS and the lunar base lasts for 316 seconds, approximately 5 min, enough for the 3 min discharge.

Table 5 - Energetic considerations per orbit.

	Per tile (Wh)	Total system (kWh)
Harvested energy	19	49.6
Energy available to transmit	11	28.7
Energy received on Moon	1.4	3.7

Table 6 - System efficiency considerations.

	Solar Panel	Energy storage	Transmitter	Beam
η [%]	25	80	19	70

The full satellite structure has been studied and to present a hexagonal geometry, 2611 tiles identical to those proposed are needed, so in total this results in $28 \times 2611 \times \frac{3}{60} = 3.7$ kWh of energy that is possible to store on the Moon, without considering the efficiency of the receiver system. So, overall considerations regarding the energy evaluation are presented in Table 5.

Finally, regarding the efficiency analysis presented in Table 6, it was concluded that the transmitter is the system component that most negatively influences the total efficiency, which has a value of 2.6 %.

4.4 Demonstrators

The same approach is being developed and tested in a laboratory environment for a similar project for power transfer. What the group has already developed is related to the solar power generator and wireless power transfer. The solar power generation has been researched, showing an increase in the PV's efficiency [17].

Regarding WPT, three different systems have been studied, one with reflectors [18, 19, 20] and two others with dielectric lenses [21, 22] at 5.8 and 24 GHz, that aim to show the importance of implementing quasioptics for increasing the transfer efficiency.

Additionally, a complete system demonstrator is being developed to show all the major system components working simultaneously. This demonstrator was designed for a 100-meter ground-based experiment, whose energy is generated by solar panels with downshifting layers and stored in battery packs. It aims to prove the concept's viability, prompting more serious research.

5. Discussion

As it was mentioned before, the sustainability issue and the awareness of the well-being of our planet and the Moon is deeply correlated with the technology proposed here.

Firstly, besides its higher efficiency, it has a particular feature: its reduced size in comparison with other systems due to the use of lenses in the antenna system. Therefore, it is not only more suited to space but also decreases the amount of material used, hence reducing the manufacturing impact it has on Nature. However, to achieve this, the complexity of the system with lenses is higher.

Secondly, it does not produce greenhouse gases which means that it is cleaner than the main energy sources like fossil fuels and nuclear energy. Indeed, this concept is nothing short of an improvement of the concept of harvesting solar energy that is well known. These satellites in space can capture a larger amount of energy, which is a step forward in comparison to what we have available now. This method is even capable of decreasing the inevitable energy loss caused by the presence of the atmosphere of Earth.

Additionally, the modular approach enables a much more efficient maintenance, repairing and replacement, in which only the strictly necessary parts will be actuated on. After the analysis of its consequences on Earth, it is possible to conclude that this modular architecture SPS system can be a two-in-one solution: the efficient concept that is proposed presents a reduced size with a low production of greenhouse gases and requirement of source materials, which contributes to the preservation of our planet.

6. Conclusions

A novel solar power satellite architecture has been presented whose main novelty is the addition of energy storage subsystems, making the solution more flexible and implementable in more scenarios.

The main motivation for this project is to supply power to targets which are in the shadow of any celestial body. Here, the chosen example was a base on the lunar surface.

Contributions have been made to solar power generation, whose efficiency can be increased by adding downshifting layers on top of photovoltaic solar panels, effectively increasing the amount of solar radiation energy that is captured by the solar cells. Finally, the quasioptical approach was implemented, providing a solution to the problem of low efficiency wireless power transfer. Using this framework, system components have been adjusted to enable low spillover losses and a significantly more compact system design.

This system architecture was modelled and simulated in a dynamic physics model, crucial for understanding how the various parameters affect each other, enabling the calculation of a power budget.

This power budget study was important to verify if this approach allows storing enough energy in the battery to run the system. Saving costs by not using mechanical systems to align the panels with the Sun and taking into account the losses already mentioned, 11 Wh per tile are available for the transmission process in each revolution, totaling 3.7 kWh being supplied to the lunar base at each 117 minutes.

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