75th International Astronautical Congress (IAC), Milan, Italy, 14-18 October 2024.

IAC-24-C3.IP.37

Study of architectures for RTG-Solar Hybrid power subsystems in space vehicles.

J. Antonio Fernández [a*], Pablo F. Miaja [a], Manuel Arias [a], Miguel F. Costales [a], Fermín Navarro-Medina [b], Carlos Ulloa [b], Manuel Diz-Folgar [b], Alejandro Camazo [b], Alejandro Gómez [b], Ramy Mesalam [c], Ovidiu Faur [d]

[a] *University of Oviedo - Power Supply Group (SEA), Campus Gijón Dep. Oeste, 33204 Gijón, Spain* fernandezalvantonio@uniovi.es
[b] *University of Vigo - Campus de Ourense, As Lagoas s/n, 32004 Ourense, Galicia, Spain*
[c] *University of Leicester - Space Park Leicester, 92 Corporation Rd LE4 5SP, Leicester, UK*
[d] *European Space Research and Technology Centre (ESTEC), European Space Agency (ESA), Noordwijk, Netherlands*
* *Corresponding Author*

Abstract

The combined use of Radioisotope Thermoelectric Generators (RTGs) alongside Solar Arrays (SAs) and batteries is a promising strategy for ensuring a reliable and sustainable power supply for space missions. While SAs harness sunlight when available, RTGs provide a continuous source of power regardless of the availability of sunlight. A battery provides for the times that the transient power demands exceed the combined SA and RTG generation. This combination offers a versatile and robust solution for the energy needs of space missions, ensuring optimal operation in a variety of conditions and locations within the solar system. An efficient design, in terms of available power and mass, of the Electrical Power Subsystem (EPS) is mandatory for the success of the mission. The different power sources must be properly managed so most of the power is available for the loads whilst keeping the sources at their most convenient operating conditions. Different architectures can be used whether they are based on a power bus voltage-regulated or on a power bus whose voltage is directly defined by one of the power sources. Regarding the RTG, one of the main concerns is adapting its low output voltage to the bus voltage. This can be done in several ways. For instance, by serializing several RTGs (efficient but introduces reliability concerns), using DC/DC conversion technologies (straightforward but increases power losses), or using partial processing techniques (reduces power loss but increases complexity). This study is to analyse each architecture to see their benefits and disadvantages and assess them qualitatively and quantitatively. Every proposed architecture is evaluated by sizing each power source and the units used to regulate them, according to different mission requirements. Then the mass and the electrical power available to the loads is computed. For that purpose, models of each component (SAs, RTGs, batteries, DC/DC converters) are used to evaluate every scenario. The results obtained on this study, are represented in a series of figures of merit, related with the mass of the power sources, the efficiency of the regulators used, the energy dissipation in terms of temperature (which can affect to the RTG behaviour), the maximum operation time and the battery time recharge.

Keywords: (maximum 6 keywords)

Nomenclature

C_{bat} – Battery capacity (Wh)
C_{cell} – Battery cell capacity (Wh)
N_S – Number of serial battery cells
N_P – Number of parallel battery cells
Pwr_{EPS} – Power demanded by the load
V_{bus} – EPS bus Voltage
V_{bat_max} – Maximum battery voltage
V_{cell_max} – Maximum battery cell voltage
V_{SA_cell} – Solar Array cell voltage
W_{SA_cell} – SA cell power at MPPT

Acronyms/Abbreviations

BCDR – Battery Charge Discharge Regulator
DoP – Deep of Discharge.
EoC – End of Charge
EPS – Electrical Power System
ESA – European Space Agency
MEA – Main Error Amplifier
MPPT – Maximum Power Point Tracking
NASA – National Aeronautics and Space Administration
PSR – Permanent Shadow Region
RTG – Radio Thermal Generator
SA – Solar Array
SAR – Solar Array Regulator
SoC – State of Charge
TEG – Thermal Electrical Generator

1. Introduction

Various rover missions, Lunar and Martian, like Curiosity, Perseverance, Yutu 1 and 2, have been carried out. These have always been powered by a single energy source, either solar energy or thermal energy generated by RTGs [1] [2]. The combined use of these two technologies is a promising strategy for ensuring a reliable power supply for space missions [3] [4]. This can be applied to lunar rovers.

The combined use of these technologies offers significant advantages for the projects that implement them, as it allows for the exploration of both sunlit areas and permanently shadowed regions. While it is true that RTG-powered vehicles can explore sunlit zones, due to the low power they generate, continuous use in these regions would not be possible. This would lead to recharge pauses similar to those that would occur in shadowed areas.

In addition to these sources, it is necessary to use batteries to help the RTGs propel the vehicle in dark areas. The way these two devices would work together involves charging the battery with the energy generated by the RTGs (with the vehicle at rest at that moment), to continue being propelled by the stored energy plus that of the RTG. This means that during these shadowed areas, the device would not operate continuously; instead, there would need to be pauses for recharging the batteries.

Analysing previous lunar missions, it can be seen that the vehicle’s operation can be grouped into four modes:

- Driving
- Battery recharging.
- Communication with Earth.
- Scientific operations: this mode encompasses the various specific operations of each mission that do not fall under any of the other three previous modes.

Reviewing documentation from these missions, it has been observed that the mode with the highest consumption of the four is driving, making this the critical design point that will be used in the following sections.

The objective of the study presented in this article is to define how these energy sources are integrated into the power management system of a lunar rover, how they are sized, and to analyse which devices may be necessary to adapt to the vehicle’s voltage bus. Section 2 explains the energy sources and proposes the possible combinations that give rise to the architectures that can be implemented. Section 3 presents the methodology for designing the system in its most critical case (driving in PSR), moving on to the Section 4 where the results obtained are presented. Finally, the results are analysed, showing the conclusions obtained.

2. Electrical Power Subsystem analysis.

The first step in designing the Electrical Power Subsystem (EPS) is to conduct a comprehensive evaluation of the potential topologies that can be implemented. This evaluation involves a detailed analysis of each energy source independently to whether its characteristics allow for setting the bus voltage or whether a regulation stage is needed to determine the bus voltage.

2.1 Solar Array characteristics.

A Solar Array (SA) cannot be directly connected to a power bus due to several critical reasons: the solar array's output fluctuates with sunlight, causing unstable voltage that can damage sensitive systems. Additionally, direct connection risks overcharging the batteries, while a Solar Array Regulator (SAR) ensures controlled charging and stable power delivery. The SAR also enables Maximum Power Point Tracking (MPPT) to optimize energy harvest and prevents current backflow from the bus to the array, which could damage the panels. Finally, the regulator converts variable solar output to the required voltage for efficient and safe system operation.

The output voltage of the SA is directly proportional to the solar radiation incident on the system, with values ranging from zero volts in Permanent Shadow Regions (PSR) to higher voltages under optimal conditions. As the scope of this paper covers the situation where the rover operates in PSR without sun power, the SA remains in a second place of design, needing the power supplied by the RTG. Nevertheless, the SAR is required for operation during sunlit.

2.2 Battery.

An electrical battery consists of multiple individual cells, and its overall voltage and capacity are determined by the configuration of these cells. A key characteristic of battery cells is that they do not maintain a constant voltage; instead, the voltage declines as the state of charge decreases. As a result, in topologies where the battery dictates the operating voltage, the EPS voltage will not remain fixed. On the other hand, directly connecting batteries to an EPS involves a straightforward setup. This method offers simplicity in implementation and minimal additional components, making it cost-effective and easy to manage. The alternative approach involves using a Battery Charge Discharge Regulator (BCDR). The BCDR acts as an intermediary device that monitors the battery's state of charge (SoC), regulates the charging and discharging currents accordingly and fix an output voltage accordingly to the EPS desired voltage.

2.3 RTG

The RTG is a device that generates electricity by converting heat released from the decay of radioactive material into electrical energy using thermoelectric converters. In opposite to SA, which generate electrical power from an outside energy source (solar radiation), RTG energy comes from the inside of the device, generating constant power. One of the advantages of the RTGs is its long-lasting life, allowing to use the RTG as main energy source. In opposition to that, one of the disadvantages of RTGs are their low output power dynamics, making them unsuitable for providing instantaneous power demands effectively.

The proposed RTG is modular, each RTG unit offers 6 individual Thermoelectric Generators (TEG). Those 6 TEGs can be connected in any series or parallel combination to achieve the desired power. On top of that several RTG units can be added to the system and thus connected in series or parallel with the rest. Effective energy management strategies are mandatory to optimize RTG utilization and minimize energy wastage. It is necessary for RTG units to have a device that continuously extracts the maximum available power, ensuring that the energy not being used by the load is dissipated outside the RTG and providing good dynamics for instant power demands. This device (from now known as RTG-Adapter) does not function as a regulator that maintains the output voltage according to the bus voltage level. Instead, it would provide an output voltage according to the maximum power being delivered by the RTG at that moment. For those reasons, RTG can be connected to the EPS bus in two ways: direct connection, setting the bus voltage with its output, or connected through a DC/DC converter, which will adapt RTG output to EPS voltage.

2.4 DC/DC Converters

In addition to the three primary energy sources, one of the key components of the EPS is the DC/DC power converter, which transforms energy source's output voltage level to EPS bus Voltage, ensuring compatibility between power sources and system components. However, their operation introduces energy losses, typically dissipated as heat. The design, size, and mass of these converters are dictated by the maximum power they are required to handle. Furthermore, their efficiency depends on the difference between input and output voltages and the load percentage relative to their total capacity. Examples of these characteristics can be found in the datasheets of these space-qualified converters [5] [6].

The adaptation to the power bus voltage can be done in several ways:

- Using DC/DC converter: this will be the straightforward way to implement a regulator. The main disadvantages associated with this device are the power losses associated.
- Partial processing technique: Partial processing refers to a method where only a portion of the input power is processed to adapt the device to the main power bus [7] [8]. In the context of RTGs, partial processing techniques focus on optimizing energy extraction from the source while minimizing losses. This approach ensures that the system operates efficiently than the DC/DC converters but adds more complexity than them. Both options have in common that the output voltage regulated providing the bus with a constant voltage.
- DCX: a DCX is a variation of a DC/DC converter, which has not feedback and the output voltage is proportional to the input. The main advantage is the efficiency is higher than a DC/DC. However, as the DCX does not perform any regulation the dynamic characteristics of the power voltage provided will be determined by the power source.

2.5 Subsystem Architectures

After defining the energy sources and their possible configurations within the EPS, the next step involves organizing the potential combinations that can be derived. Figure 1 presents the resulting architectures diagrams that can be implemented based on these configurations.

2.5.1 BusReg

The bus voltage is regulated. Each of the sources (SA, RTG, Battery) will have a dedicated regulator. A Main Error Amplifier (MEA) will sense the bus voltage and demand the required amount of power from all the sources to keep the bus voltage regulated regardless of the load demand. Priority among the sources will be established in such a way that the RTG always provide power to the bus whilst the remaining will be either supplied by the SA or the battery.

2.5.2 BusBat

The battery will determine the bus voltage unless it has reached its EoC voltage. In this case the RTG-Regulator or the SAR will regulate its power to regulate the battery voltage. A system, in the fashion of the MEA, will be needed to determine how much power each of the sources will deliver, giving priority to the RTG.

2.5.3 BusTEG

The voltage of the bus is determined by the TEG in the RTG. It may be possible that the bus voltage needs to be lower than typical buses (28 V), so this will have an impact on the rest of the converters. The SAR and BCDR will provide the rest of the power to meet the demand.

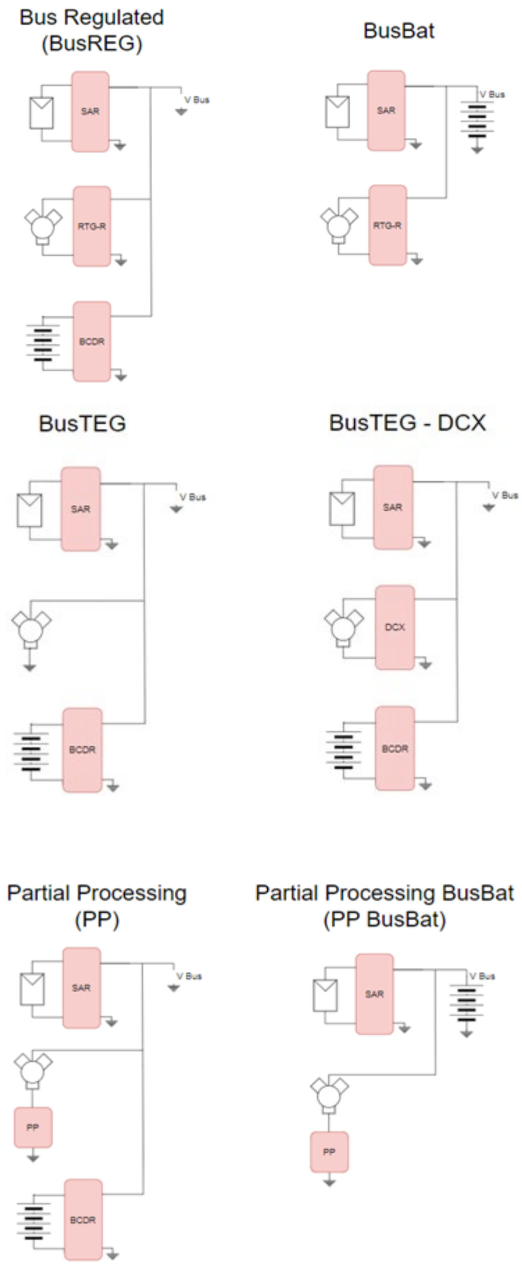

Figure 1. Architectures diagram.

2.5.4 BusTEG DCX

This architecture is analogous to the *BusTEG* one. However, the DCX offers a degree of freedom since it introduces a scaling between the optimum TEG output voltage and the desired bus voltage [9] [10]. AS the DCX is unregulated it can be optimized for efficiency. However, the bus voltage will follow the TEG voltage. This configuration will avoid connecting too many TEGs in series. SAR and BCDR will provide the remaining power for supplying the demand.

2.5.5 Partial processing

In this architecture the bus voltage is regulated. However instead of all the RTG power being transformed, only a part of it will undergo a conversion. This conversion will make sure that the RTG voltage remains compatible with the bus voltage. This will increase the efficiency of the system at the cost of an increased complexity. It may be possible that the power processed to raise the RTG voltage comes from the bus.

2.5.6 Partial processing BusBat

This architecture leverages from the *BusBat* one. It incorporates the mentioned partial power processing to bring the RTG output voltage to the battery EoC.

2.6 Objectives of the analysis:

The purpose of the study is to evaluate each architecture against a predefined set of figures of merit (FOM), which evaluates various performance metrics, quality indicators, and efficiency measures relevant to the specific application domains. For the architectures presented on Figure 1, the FOM evaluated are:

- Efficiency: this metric represents the relation between the power available for the load and the total power sources installed to fulfil the power demand (Power Available / Installed Power).
- Mass: the weight of all the components is evaluated and added to perform a total sum of the mass in the system needed for fulfilling the power demand requirements.
- Power dissipated (W): this metric represents the amount of energy dissipated in the system. It will serve to inform the Thermal model, which in turn impacts the power budget.
- Operation time: This metric is taken in the operation without sunlight in a permanent Shadowed Region (PSR) represents the time that the rover can operate with battery and RTG power.
- Recharge time: battery time recharge in PSR mode, only with RTGs.
- Available Power RTG / Installed Power RTG: this metric represents the ratio between the maximum electrical power that can be delivered to the bus from the RTG divided by the installed electrical power coming from RTG.

These FOM are determined by the following variables:

- EPS bus Voltage.
- Number of RTG units installed: this element determinates the charge time in PSR.
- Battery capacity: this parameter, along with RTGs, determine the operation time in PSR.

- SA size: determine the operation and charge times in illuminated regions.

The objective is to adjust the variables for different combinations, thus creating various scenarios allowing an independent evaluation of each architecture. The weighting of each FOM in the final evaluation of the architecture will depend on the project's specific requirements. For instance, if a lightweight design with a good W/kg ratio is needed, or if weight is less critical but long operational time in PSR is required. Furthermore, the evaluation framework ensures that assessments align closely with mission objectives and desired outcomes, guiding decision-making processes effectively.

3. Energy sources evaluation.

The first step is to evaluate each energy source independently, to see its possible combinations and designs.

3.1.1 RTG Sizing.

As mentioned in Section 2, the RTG units are composed of 6 TEGs, which are responsible for generating electrical energy. Each TEG is an independent power source, which generates 2 V and 1 A in its Maximum Power Point (MPP), 2W. The configuration of these devices plays a crucial role in the efficiency of the energy extracted from the RTG unit. On one hand, for architectures where the EPS voltage is determined by an external source, the higher the voltage extracted from the RTG, the fewer losses will be generated by the DC/DC converter. On the other hand, when multiple TEGs are connected in series, a failure in one will result in an open circuit, disabling the rest of the TEGs in the series.

Below is a list of the four electrically possible configurations:

- 1s (serial) 6p (parallel): 2 V - 6 A - 12 W
- 2s 3p: 4 V - 3 A - 12 W
- 3s 2p: 6 V - 2 A - 12 W
- 6s 1p: 12 V - 1 A - 12 W

As it can be seen, with independence of the configuration, the maximum power available will always be extracted from the RTG. The advantage of connecting each TEG in series is that if one of them fails, it does not affect the performance of the other TEGs. The RTG will still provide 2 V, but in this case, only 5 A (10 W). However, the disadvantage of this configuration is that the voltage difference between the RTG and the EPS becomes larger. An electrical power converter must be placed between these two points, and the greater the voltage difference, the lower the efficiency of the converter. Here's how each configuration would behave in the event of a TEG failure:

- 1s 6p would change to a 1s 5p configuration.
- 2s 3p would become 2s 2p. 2 TEG less.
- 3s 2p would become 3s 1p. 3 TEG less.
- 6s 1p: In this case, the failure of one TEG would result in a total RTG failure.

The following image presents a comparison of the different FOM for these four scenarios when one of the TEGs fails.

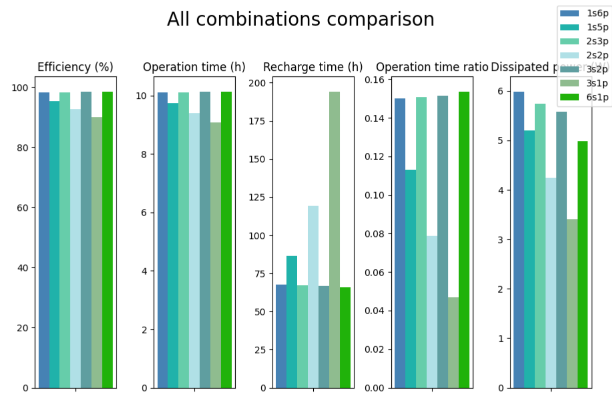

Figure 2. TEG failure comparations.

As it can be seen, parameters such as efficiency and operational time improve connecting more TEGs in serial, resulting in better overall performance. Additionally, it can be observed that when a TEG fails in the various configurations, the impact on performance is significant, leading to notably longer battery recharge times. Selecting the property configuration is critical for the interests of the project, and must be

3.1.2 Battery sizing.

The objective of this section is to determine the optimal battery capacity needed to achieve the desired operation time for the vehicle, ensuring that the battery is properly sized to meet performance requirements. The battery will function as the primary power source during periods without solar energy in conjunction with the RTGs. The objective is to size the battery to ensure continuous operation of the lunar rover over a defined period. To accurately size the system, it is necessary to determine the total power demand, which is calculated as the rover's power consumption minus the power provided by the RTGs.

When battery cells are connected in series, their voltages and capacities (in Wh) add together, resulting in a higher overall voltage. Conversely, when cells are connected in parallel, their capacities are combined, increasing the overall energy storage capacity, while the voltage remains the same as that of a single cell. By configuring cells in different series and parallel arrangements, the battery's voltage and capacity can be tailored to meet specific operational requirements, which can be different depending on the topology selected. These architectures, explained on section 2, can be grouped in two types: the ones which includes a BCDR and the ones with an EPS bus regulated by the battery

In the first scenario, it is critical to ensure that the battery's maximum voltage remains lower than the regulated EPS voltage. This configuration simplifies the BCDR design by allowing it to consistently function as a step-up converter during energy discharge to the EPS and as a step-down converter during battery charging. To set number of cells to be connected in series, the EPS voltage should be divided by the maximum voltage of a single cell, with the result rounded down to the nearest integer:

$$\lfloor N_S \rfloor = \frac{V_{bus}}{V_{cell\_max}} \quad (1)$$

The number of blocks connected in parallel is the capacity desired divided by the capacity per serial block:

$$\lceil N_P \rceil = \frac{C_{bat}}{C_{cell} * N_S} \quad (2)$$

In the case when the battery sets the EPS Voltage, it's important to consider that the battery cell voltage fluctuates based on its charge level. As a result, the voltage in the EPS will not remain constant, requiring the other regulators within the EPS to adjust accordingly. To calculate the number of cells connected in serial, it is necessary to set the maximum voltage that the battery has to operate. The number of cells connected in parallel is calculated as exposed on (2).

3.1.3 Solar array sizing.

Similar to batteries, SA consist of cells that can be arranged in series or parallel to produce various voltage and current combinations. In this project, the critical design point focuses on rover operation during PSR. Therefore, the SA is dimensioned last, as its role is to enable continuous driving in sunlit areas alongside RTGs without relying on battery power.

Two key parameters must be considered during design: the bus voltage and the power required by the load. Knowing the minimum bus voltage—whether it's the minimum battery bus voltage or a regulated, stable voltage—helps determine the number of series-connected cells, similar to battery sizing. The goal is to generate a voltage close to, but always below, the bus voltage to ensure efficient operation, as most solar array regulators (SARs) are step-up type DC/DC converters, elevating the voltage between the SA and the EPS. Equation (3) represents how to calculate the number of cells connected in serial:

$$\lfloor N_S \rfloor = \frac{V_{bus}}{V_{SA\_cell}} \quad (3)$$

The next step involves calculating the number of cell blocks that need to be connected in parallel to meet the power demand of the load. This is determined by subtracting the power provided by the RTGs from the rover's power consumption in driving mode. The number of cells connected in parallel can then be calculated using the following method:

$$\lceil N_P \rceil = \frac{Pwr_{EPS}}{W_{SA\_cell} * N_S} \quad (4)$$

In this way, the solar panel is dimensioned to work in conjunction with the RTGs, allowing the rover to drive continuously without interruption.

4. Architectures studied.

After grouping the different architectures based on their characteristics and behaviours, the subsequent step involves conducting a static test. This test serves as a pivotal phase in the evaluation process, offering insights into how each architecture performs under controlled conditions. The static test will be conducted using Python programming language through Jupyter notebooks, which provides a versatile and interactive platform for executing test scenarios, analysing results, and iterating upon the evaluation process efficiently.

4.1 Optimal design for each architecture.

The objective of this section is to evaluate the architectures defining an operation time for the rover and sizing the energy sources according to that for the different architectures. As discussed in Section 1, the rover's most power-intensive and critical operating mode is its driving mode. Therefore, the energy consumption in this mode will be used as a reference for sizing the power sources in the tests conducted in this section: 500 W.

The first step is to configure the RTG output. As it has been exposed, it can be connected to the EPS bus in 4 ways: the three types of converters described in Section 2.4 and direct connection. The difference between them lies in the efficiency and mass of the additional device introduced. This is determined by the difference between the RTG's output voltage and the voltage of the bus to which it will be connected. For this test, a bus voltage of 28 V is selected for the regulated topologies, a standard commonly implemented in many satellites. Table 1 illustrates the energy conversion efficiency for each type of connection and for various combinations of the TEGs that form the RTG, as described in Section 3.1.1. It is important to note, that each RTG has its own converter

Table 1. RTG efficiencies.

		Direct	DC/DC	DCX	Partial
Conf.	**Vin**	**Eff**	**Eff**	**Eff**	**Eff**
1s 6p	4.75	100	92.3	96.20	70.10
2s 3p	9.51	100	92.6	96.25	87.72
3s 2p	14.26	100	92.9	96.31	93.32
6s 1p	28.52	100	93.7	96.38	95.00

After analysing the efficiency of the RTGs based on how they are connected to the EPS, the next step is to determine the power demand for each architecture depending on the RTG configuration. The power demand is calculated by subtracting the power supplied by each RTG (12 W at MPP), after accounting for losses, from the power required by the load in driving mode (500 W). Table 2 illustrates how this demand changes for a range of RTG configurations, from 4 to 8 RTGs. RTGs will be configured in a 3s 2p arrangement for the power calculations. This configuration provides good performance in all cases; in contrast, a 6s 1p setup will result in a total RTG failure if a single TEG fails.

Table 2. Battery power demanded.

	RTG Units				
	4	**5**	**6**	**7**	**8**
BusReg	455,41	444,26	433,11	421,96	410,82
BusBat	455,41	444,26	433,11	421,96	410,82
BusTEG	452,00	440,00	428,00	416,00	404,00
BusTEG DCX	453,92	442,40	430,88	419,36	407,84
PP	455,84	444,80	433,76	422,72	411,68
PP-BusBat	455,84	444,80	433,76	422,72	411,68

The next step is to size the battery. Calculate the power demanded by the load, considering the RTG power supplied to the EPS in each architecture. This requires determining the total energy that needs to be stored, which is done by multiplying the power demand by the total operational time (in seconds) required for the rover. For this test, rover target is to drive in PSR mode for 2 hours. In comparison with other rover missions, it is a very long duration. However, it was decided to do so in order to have a very big margin. This will be refined in further studies.

To size the battery, it is necessary to select an EPS voltage. Select a standard regulated bus. In this type of EPS, a typically voltage bus is 28. For the regulated bus, this is going to be the voltage. In the case of topologies where the battery regulates the V_{bus}, the max value is set to 32 V, to have a mean voltage value near to 28 V. With voltage information, the number of cells can be calculated with equations (1) and (2). From Table 3 to Table 8 present the results after calculating the number of cells needed, the total capacity of the battery calculated and its weight along with the RTGs. The test has been conducted using from 4 to 8 RTGs. A python program has been developed to compute the energy source models and calculate power losses to approach the results. This program is based on the mathematical models of the energy sources and the DC/DC converters. This application simulates the power flow form the rover load and the recharge process, calculating the power losses in all the elements and then calculating the FOM. With the battery sized, the RTG selected, the next step is to execute the application and compare the results in all the architectures. Results are presented on Figure 5.

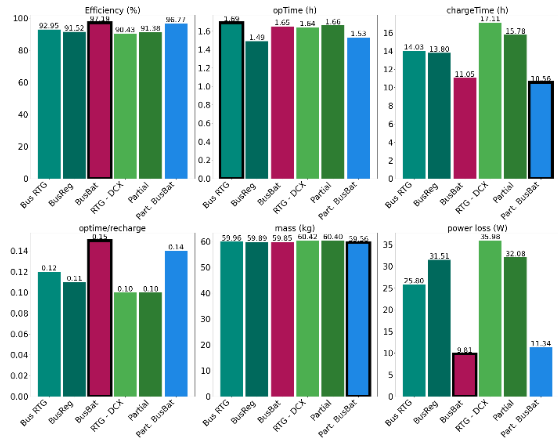

Figure 3. Architectures evaluation 2h driving.

To evaluate these FOM, a Pareto evaluation must be applied. This method involves balancing multiple performance metrics by giving them weights based on their importance for the specific application. For instance, if system efficiency is critical, it may be assigned a higher weight than power dissipation or operational time. The Pareto analysis identifies configurations where improvements in one metric can no longer be made without negatively affecting others. By adjusting these weights, we can focus on optimizing the system for the most critical FOMs to meet the design objectives. As example, the following weights were given to the results presented on Figure 5:

- Eff: 25 %
- Power loss: 5 %
- Operation time: 20 %
- Recharge time: 20 %
- Ratio Operation/Recharge: 25 %
- Mass: 5 %

Results after applying these weights are presented on Figure 6.

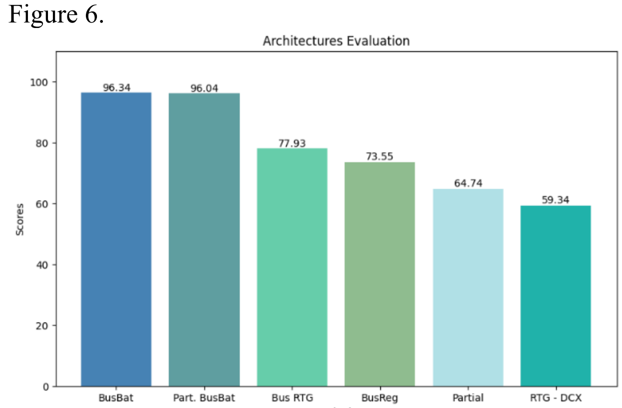

Figure 4. Pareto evaluation 1 - 2h driving test.

Table 3. BusReg battery sized for 2H.

	RTG Units				
	4	5	6	7	8
Cap (Wh)	680,4	680,4	642,6	604,8	567,0
Mass Bat + RTG (Kg)	49,06	60,14	70,98	81,82	92,65
Ns	6	6	6	6	6
Np	18	18	17	16	15
Total cells	108	108	102	96	90

Table 4. BusBat battery sized for 2H.

	RTG Units				
	4	5	6	7	8
Cap (Wh)	661,5	617,4	617,4	573,3	529,2
Mass Bat + RTG (Kg)	48,76	59,56	70,65	81,44	92,23
Ns	7	7	7	7	7
Np	15	14	14	13	12
Total cells	105	98	98	91	84

Table 5. BusTEG battery sized for 2H.

	RTG Units				
	4	**5**	**6**	**7**	**8**
Cap (Wh)	680.4	642,6	642,6	604,8	567,0
Mass Bat + RTG (Kg)	48,70	59,45	70,45	81,20	91,95
Ns	6	6	6	6	6
Np	18	17	17	16	15
Total cells	108	102	102	96	90

Table 6. BusTEG-DCX battery sized for 2H.

	RTG Units				
	4	**5**	**6**	**7**	**8**
Cap (Wh)	718,2	680,4	642,6	642,6	604,8
Mass Bat + RTG (Kg)	49,32	60,16	71,00	82,09	92,93
Ns	6	6	6	6	6
Np	19	18	17	17	16
Total cells	114	108	102	102	96

Table 7. PP battery sized for 2H.

	RTG Units				
	4	**5**	**6**	**7**	**8**
Cap (Wh)	680,4	680,4	642,6	604,8	604,8
Mass Bat + RTG (Kg)	49,06	60,14	70,98	81,82	92,93
Ns	6	6	6	6	6
Np	18	18	17	16	16
Total cells	108	108	102	96	96

Table 8. PP-BusBat battery sized for 2H.

	RTG Units				
	4	5	6	7	8
Cap (Wh)	661,5	617,4	617,4	573,3	529,2
Mass Bat + RTG (Kg)	48,76	59,56	70,65	81,44	92,23
Ns	7	7	7	7	7
Np	15	14	14	13	12
Total cells	105	98	98	91	84

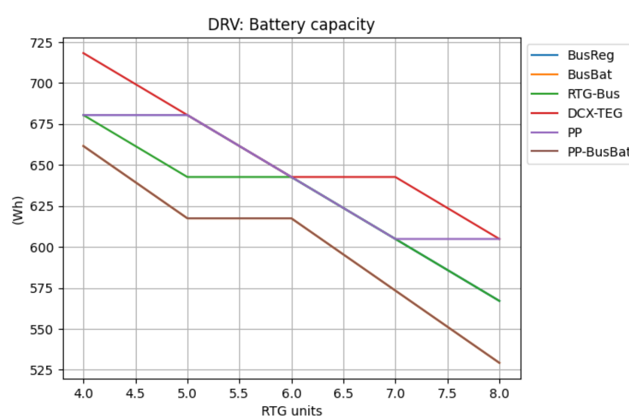

Figure 5. Battery capacity for every architecture.

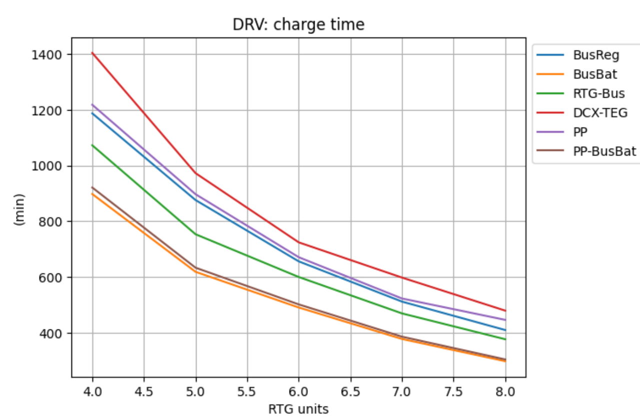

Figure 6. Charge time for every architecture.

If the following example, weights give more imporatant to mass and power dissipation. Results after applying these weights are presented in Figure 7:

- Eff: 20 %
- Power loss: 20 %
- Operation time: 10 %
- Recharge time: 10 %
- Ratio Operation/Recharge: 10 %
- Mass: 30 %

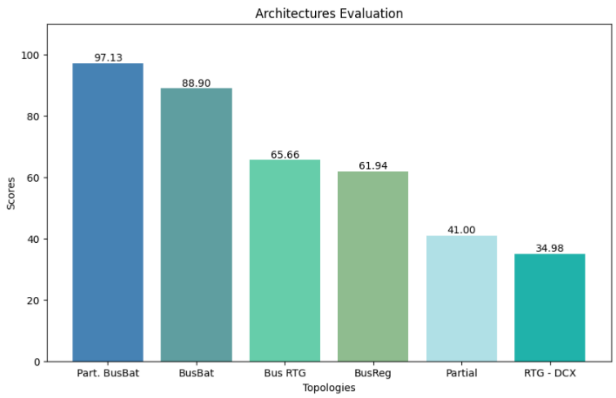

Figure 7. Pareto evaluation 2 - 2h driving test.

4.2 Common conditions for every architecture.

In this section, a test has been chosen where equal energy source sizes and system environmental conditions are applied across all architectures. This standardized approach ensures a fair comparison, enabling an independent evaluation of each architecture, offering a different perspective on the system. It allows for maximizing performance based on defined equipment and conditions. Below is a list of the default parameters configured for the test:

- 5 RTGs
- Battery capacity: 4 kWh
- Solar array size:
- EPS V_{bus}: 28 V

The design process is omitted for this test since all energy sources are pre-dimensioned. The only components that need to be designed based on the initial conditions are the DC/DC. The design process for these power electronics converters is incorporated into the Python application developed for this project, as previously mentioned. The objective of the test is to evaluate every topology for the worst scenario: rover driving on PSR without sun power. The FOM results obtained under these conditions, after executing the Python application, are shown in Figure 8.

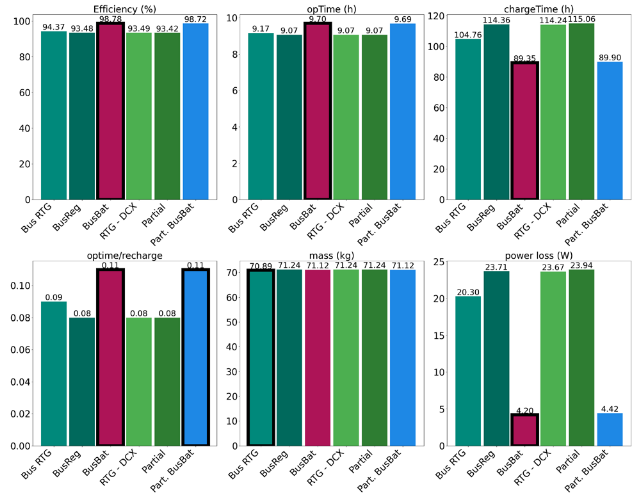

Figure 8. Architectures evaluation results. Common parameters.

As example, the following weights were given to the results presented on:

- Eff: 25 %
- Power loss: 5 %
- Operation time: 20 %
- Recharge time: 20 %
- Ratio Operation/Recharge: 25 %
- Mass: 5 %

Replicating the Pareto analyses performed in the previous section using the same weights, the results are presented in Figure 9 and Figure 10.

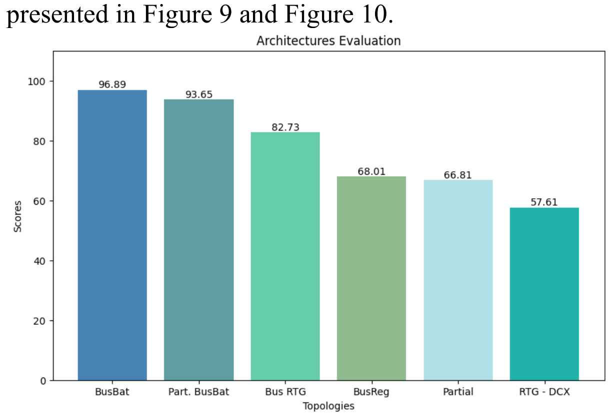

Figure 9. Pareto evaluation 1 - Common parameters.

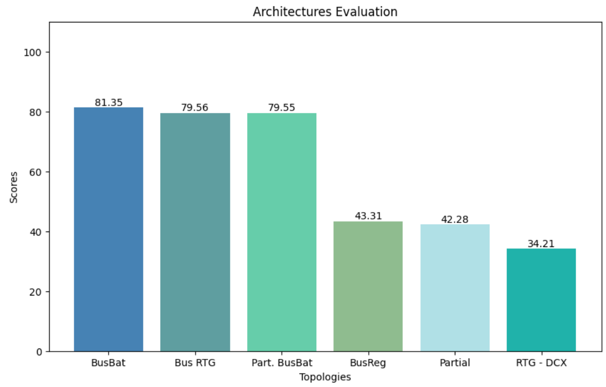

Figure 10. Pareto evaluation 2 - Common parameters.

5. Discussion

The initial analysis of the results shows that both the BusBat topology and the PP-BusBat offer the best performance in the figures of merit, as seen in both raw data and Pareto evaluations. This is primarily because DC/DC converters are the main sources of energy loss, with the BCDR transferring the most power in these configurations. The systems studied involve batteries ranging from 600 Wh to 4 kWh, delivering significantly more power (340 W load consumption) compared to the RTGs (around 12 W). This creates a variable EPS bus voltage, which adds complexity to the design of power converters connected to the bus.

When comparing the BusBat and PP-BusBat topologies directly, the PP-BusBat shows better performance in certain conditions, particularly with a 3s 2p RTG configuration. This setup was selected for the study because others with more RTGs in parallel and fewer in series showed significantly lower performance when using partial power processing, leading to the exclusion of those architectures.

Given that the projects targeted by this study are highly specialized and involve significant time and financial investments, the designs are tailored to each individual project, making it difficult to establish a standard approach. Therefore, in practice, the design process will follow the method described in Section 4.1.

The purpose of the analysis in Section 4.2 is to evaluate all topologies under the same conditions, validating the results from Section 4.1 and providing a comprehensive overview of the performance of each topology. The results obtained in this global evaluation closely align with those from the specific design, further validating the conclusions.

6. Conclusions

The main conclusions of the study are:

- The Battery Bus configuration is consistently the best-performing option in Pareto analyses, making it the most viable choice.
- Partial processing techniques can be ideal under specific circumstances, particularly when RTGs are arranged in a 3s2p configuration and mass is a critical factor in Pareto analysis. In most other scenarios, conventional DC/DC converters provide superior results.
- DCX transformers with RTGs yield the poorest results in Pareto evaluations, demonstrating higher losses and inefficiencies.
- The use of these topologies requires two devices for the RTGs: the RTG-Adapter and the DC/DC converter. This setup opens up an opportunity for future work by merging these two components into a single device. Such integration could optimize performance by reducing the number of conversion stages, minimizing energy losses, and improving overall efficiency. Additionally, combining these functions into one unit could simplify the system design, reduce mass and volume, and offer enhanced reliability, making it an appealing direction for future research and development in power systems.

Acknowledgements

This work has been financed by the European Space Agency (ESA), under the project "Power management & conditioning for Hybrid Radioisotope-Solar power systems" and the Spanish minister of science, innovation and universities, though the project "Nuevas topologías para un sistema de distribución secundario estandarizado en satélites" MCIU-22-PID2021-127707OBC21 and the FPI grant MCINN-23-PRE2022-101790.

7. References

[1] L. Summerer, J. Pierre Roux, A. Pustovalov, V. Gusev, y N. Rybkin, «Technology-based design and scaling for RTGs for space exploration in the 100 W range», *Acta Astronautica*, vol. 68, n.º 7-8, pp. 873-882, abr. 2011, doi: 10.1016/j.actaastro.2010.08.020.

[2] V. P. Friedensen, «Space nuclear power: Technology, policy, and risk considerations in human missions to Mars», *Acta Astronautica*, vol. 42, n.º 1-8, pp. 395-409, ene. 1998, doi: 10.1016/S0094-5765(98)00134-9.

[3] A. Baraskar, Y. Yoshimura, S. Nagasaki, y T. Hanada, «Space solar power satellite for the Moon and Mars mission», *Journal of Space Safety Engineering*, vol. 9, n.º 1, pp. 96-105, mar. 2022, doi: 10.1016/j.jsse.2021.10.008.

[4] T. Widdicombe y R. A. Borrelli, «MCNP modelling of radiation effects of the Dragonfly mission's RTG on Titan», *Acta Astronautica*, vol. 183, pp. 363-373, jun. 2021, doi: 10.1016/j.actaastro.2020.12.033.

[5] «DS-SGRB10028S-3.0_54379.pdf».

[6] «SA50-28-Single-Series-Data-Sheet-DS00003892.pdf».
[7] C. Li, Y. E. Bouvier, A. Berrios, P. Alou, J. A. Oliver, y J. A. Cobos, «Revisiting "Partial Power Architectures" from the "Differential Power" Perspective», en *2019 20th Workshop on Control and Modeling for Power Electronics (COMPEL)*, Toronto, ON, Canada: IEEE, jun. 2019, pp. 1-8. doi: 10.1109/COMPEL.2019.8769667.
[8] J. R. Rakoski Zientarski, J. R. Pinheiro, M. L. Da Silva Martins, y H. L. Hey, «Understanding the partial power processing concept: A case-study of buck-boost dc/dc series regulator», en *2015 IEEE 13th Brazilian Power Electronics Conference and 1st Southern Power Electronics Conference (COBEP/SPEC)*, Fortaleza: IEEE, nov. 2015, pp. 1-6. doi: 10.1109/COBEP.2015.7420092.
[9] A. López, T. H. Oliveira, M. Arias, P. F. Miaja, J. A. Villarejo, y A. Fernández, «Modular Fault Tolerant DC/DC Transformer Enabled by Natural Power Sharing», *IEEE Open J. Power Electron.*, vol. 5, pp. 902-919, 2024, doi: 10.1109/OJPEL.2024.3414141.
[10] H. Chen, K. Sabi, H. Kim, T. Harada, R. Erickson, y D. Maksimovic, «A 98.7% Efficient Composite Converter Architecture With Application-Tailored Efficiency Characteristic», *IEEE Trans. Power Electron.*, vol. 31, n.º 1, pp. 101-110, ene. 2016, doi: 10.1109/TPEL.2015.2398429.