Executive Summary Report

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Lunar ISRU Energy Storage and Electricity Generation (LIESEG) project (ESA Contract Nr. 4000124000/18/NL/AF)

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1 - Introduction

Humankind tested its capacity to survive on the Moon's surface for short periods of time in the Apollo missions almost 50 years ago. Since then, robotic missions to the Moon have spent several days and nights in the satellite. However, many technological challenges arise when planning a lunar (robotic and/or manned) mission fully operational during the night. Among these challenges, the need of a power supply system for both day and night remains open.

Figure 1 shows the relation between the mission objectives, energy requirements and power generation and storage systems for missions in the Moon. The energy requirements (which can be thermal and/or electrical) of a lunar mission are determined by several factors such as the landing site, lunar environment, span and profile of the missions, and whether it is robotic and/or manned. The energy requirements include the needs of both power generation and storage. There are several technological candidates for these two functions. This document focusses on the analysis of these technologies and in the computational simulations of one of the most appropriate sets of technologies.

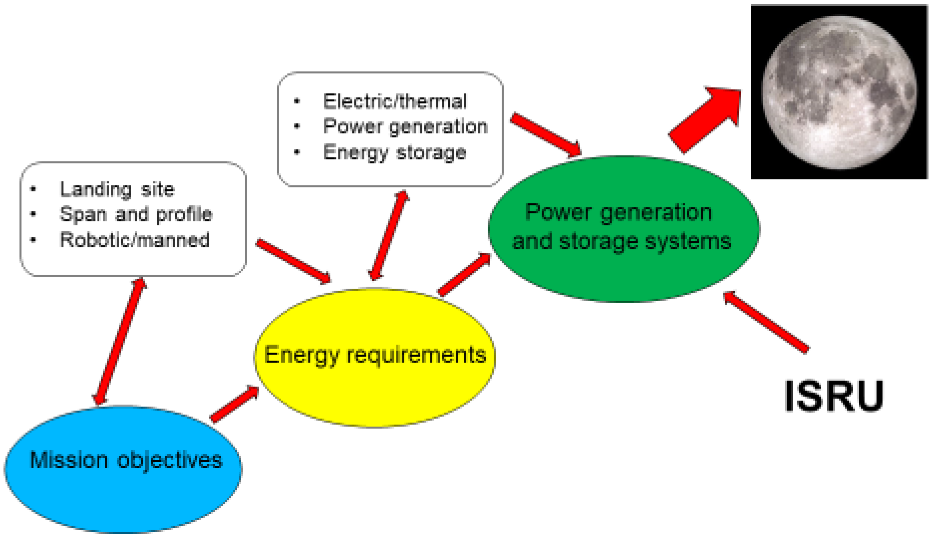

Figure 1: Relationship between mission objectives, energy requirements and power generation and storage systems for missions in the moon.

2 - Power requirements

The analysis of data from literature and current and past plans of space agencies about moon missions power demands suggests to differentiate between the following types of missions:

- Precursors: missions carried out by rovers (and in a longer term also by humans) as precursors of lunar settlement missions.

- Lunar settlements: missions carried out by humans and rovers in which, among other operations, a habitat is developed. These missions take advantage of the operations carried out by the precursor missions.

Table 1 shows a summary of the characteristics of the considered precursor missions. The power requirements range between the tens of Watts for small exploration rovers to some thousands of Watts for manned rovers in the first outposts. These values correspond to rovers in operation; the power consumption will be even smaller if they are in sleeping mode during the night.

Mission/Rover	Power Source	Night Survival	Weight (Kg)	Power (We)
Lunar Rover Vehicle	Battery	No	210 + 490	~1000
Lunokhod 1	Solar + Battery	RHU	810	< LRV
Chang'e 3	Solar + Radioisotope (Lander) Solar + Battery (Rover)	RHU (both)	140 (Rover)	~148
Chandrayaan 2	Solar	No	17	~33
SELENE 2	Solar + (?)	Night survival module	100	~110
Lunar Prospector	Solar	No	300	300
Rover design	Solar + Battery	Battery recovery design	25	40
Rover (lunar outpost)	Rechargeable Batteries	Sleep mode at the outpost	1240	1400 to 2700

Table 1: Main characteristics of the selected precursor missions.

Table 2 shows a summary of the power consumption of lunar outpost missions at different stages. As a general rule, in the first stages the power consumption of the outpost is reduced at night (up to 50%) because part of the base equipment enters into a sleep mode to survive the night.

Larger lunar settlements will have continuous working facilities as laboratories, ISRU centers or larger habitats. Therefore, the variation of the consumption between day and night will grow thin. Due to the increasing power requirements in successive stages, larger power generators will be needed with time. The use of nuclear power could be considered, but building a nuclear plant could be expensive, rather complex and potentially hazardous. An alternative is the use of the energy supplied by the Sun.

Study	1st stage consumption (kWe)	2nd stage consumption (kWe)	Early power source	3rd stage consumption (kWe)	Next stages consumption (kWe)	Later power source
D.A. Petri et al. [1]	25(D)/12(N)	80(D)/50(N)	PV/RFC	180(D)/150(N)	200 extra or more	PV/RFC + Continuous
R.L. Cataldo et al. [2]	12(D)/11(N)	-	-	-	-	-
L. Mason et al. [3]	30	80	nuclear	-	-	nuclear

Z. Khan et al. [4]	-	81 (Day)	PV/RFC	more	-	nuclear
G.A. Landis [5]	-	100(D)/50(N)	Undefined	more	-	-
T.S. Balint [6]	From few to 100		Solar and radioisotope	100+	-	others
Apollo [7] [8]	1 - 4	-	Fuel cells / Batteries	-	-	-

Table 2: Power consumption of lunar settlement missions at different stages.

Information provided by Table 2 and Figure 2 are the reference of power demands for the computational work in this project. In particular, the night power requirements considered in this work are of the order of 10 kWe (stage 1), 30 kWe (late stage 1), and 50 kWe (stage 2).

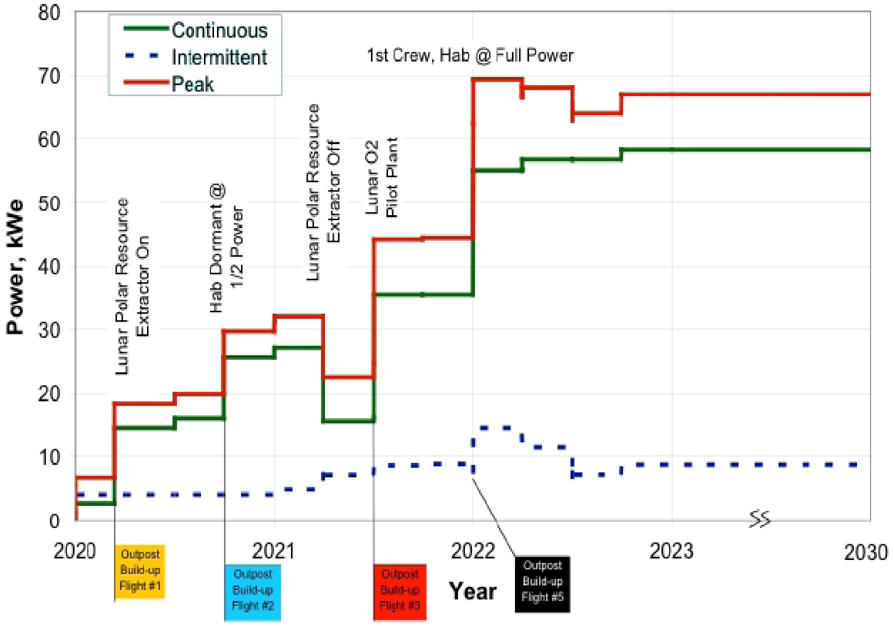

Figure 2: Lunar outpost power requirements [9].

3 - System architecture

The long nights in the satellite negate many of the advantages of the solar panels for a continuous power supply. They would only be used during the day, while other systems would be required for the night. Solar panels can be useful near the peaks of eternal light, but a technology that allowed us to generate electricity during the lunar night would add much more flexibility to the choice of location of the settlement.

Based on the work of Climent *et al.* [10], we define the system concept of the night-time power generation system for a lunar settlement as a double-loop, one in the hot side of the system and the other one in its cold side (Figure 3). The system is composed of subsystems to perform the following tasks: Solar energy collection, Heat transport, Energy storage, Heat-to-electricity conversion, and Heat rejection or release. The first loop of the system transfers heat from the solar energy collector to the energy storage and to the heat-to electricity converter. The second loop transfers heat from the cold side of heat-to-electricity converter to the heat rejection system.

An additional path could be included for daytime energy generation, transferring some of the collected heat directly to the heat-to-electricity converter of choice. Future analysis during the simulation phase will determine the most adequate system to use for electricity generation during the day.

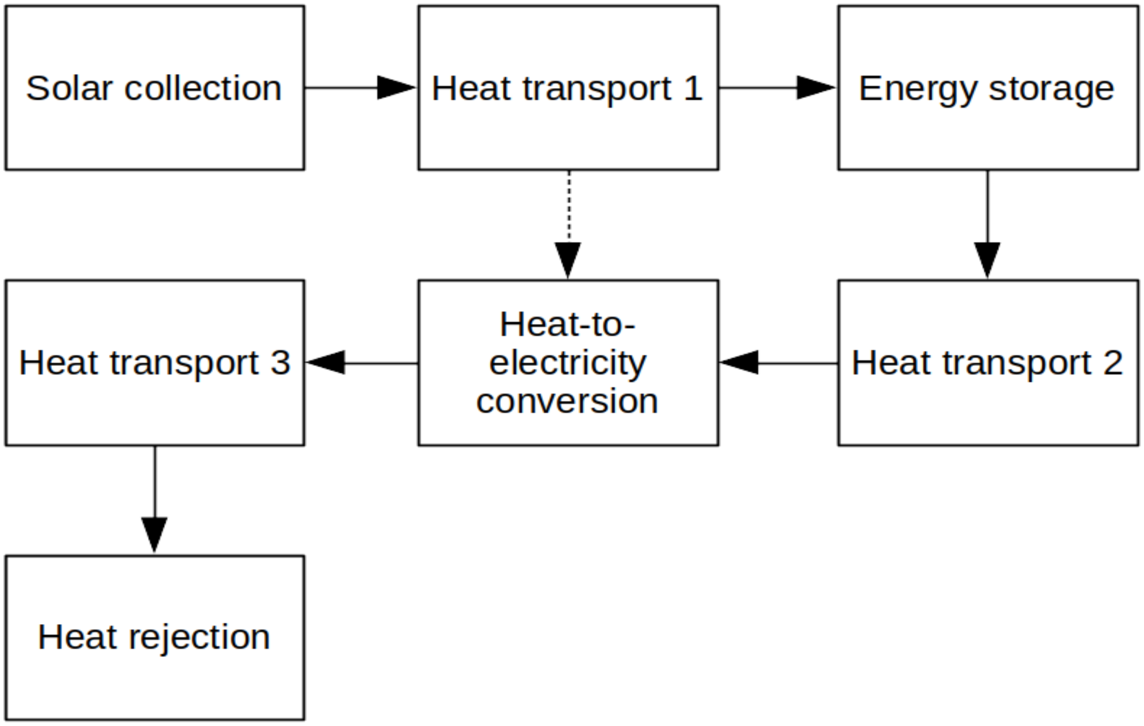

Figure 3: Simplified power generation system concept. The dashed line represents the optional daytime path.

Several terrestrial technologies can be considered for each of the subsystems.

The following technologies have been considered for the Solar energy collection subsystem: Linear Fresnel reflectors, Central receiver, Parabolic troughs, Parabolic dish, Off-axis solar concentrator, Fresnel lens.

The following technologies have been considered for the Heat transport subsystem: Heat pipes, Loop heat pipes, Pumped Loops, Direct illumination, Optical waveguide, Metal bars.

The following options have been considered for the Energy storage subsystem: Loose regolith, Sintered regolith, Molten regolith, Loose and sintered regolith with metal fins.

The following technologies have been considered for the Heat-to-electricity conversion subsystem: Heat engines (Stirling, Thermoacoustic, Brayton, Rankine), Direct heat-to-electricity converters (Thermoelectric, thermoionic and thermophotovoltaic).

The following options have been considered for the Heat rejection subsystem: Radiator / Shielded radiator / Radiator in eternal darkness, Loose regolith.

4 - **Trade-off analysis**

A trade-off analysis of the identified technological options has been carried out for each subsystem and for the full system. Common criteria are defined for all the subsystems and specific criteria only for some of them. A weight is assigned to each criterion, which may differ in each subsystem. Technologies/components are scored for each criterion. The addition of the score in each criterion provides a final score of the technology. After the analysis of the technologies, an overview of the full system considering the technologies with the highest score is presented. The full system analysis is based on the need of a correct interface between technologies, fulfilment of the power requirements, and ISRU.

The following common criteria have been taken into account in the trade-off analysis of all the subsystems.

- **Transport from Earth:** difficulty and cost of the transport of the component from Earth. It takes into account mass, storage volume, robustness, and risks involved in launch.
- **Installation and construction:** complexity of the construction and installation of the component as well as the associated risks.
- **Operation and maintenance:** difficulty of operation, amount of human intervention required, complexity of repairs.
- **ISRU:** amount of local materials used.
- **Scalability:** feasibility of an expansion of the capabilities of the subsystem.
- **Lifespan:** expected duration of the component before repairs or replacement.
- **End of life:** usefulness of the components after decommission.
- **Cost:** cost of development and operation.
- **TRL:** technology readiness level.
- **Technology maturity on Earth:** stage of development, proven capabilities.
- **Operational in high/low temperatures:** ability to operate, or at least survive, on specific extreme thermal conditions.

The following specific criteria have been taken into account only in the trade-off analysis of some subsystems.

- **Concentration ratio:** geometric concentration ratio (ratio between the collector aperture and the surface area of the receiver). Applicable to subsystem: **Solar energy collection.**
- **Performance/Efficiency:** power output to power input ratio. Applicable to subsystems: **Heat transport, Heat-to-electricity conversion, and Heat rejection.**
- **Power** and **Specific power:** total power generated and power-to-mass ratio. Applicable to subsystems: **Heat-to-electricity conversion.**
- **Volumetric heat capacity** and **Thermal conductivity:** thermal properties. Applicable to subsystems: **Energy storage** (thermal masses) and **Heat rejection.**

Most of the scores for the criteria of the considered technologies/component in the different subsystems are assigned after a qualitative analysis of the technology/component. However, in some cases, quantitative scoring rules have been considered.

All technologies receive a score between 0 and 5 in each criterion, except in the non-applicable (n/a) cases. The final score is calculated using Eq. 1, which gives the addition of all the scores times their weights, and then multiplied by the total number of criteria of the particular trade-off and divided by the number of applicable criteria. This is meant to give a fair score to those technologies that are so different to their equivalents that they do not fit in the trade-offs, like Direct illumination of thermal masses, for example. If only a few criteria were applicable to a technology, but its few scores were high in categories with high weight, then the resulting score would also be very high.

$$Total = \frac{\#criteria}{\#\ applicable\ criteria} \cdot \sum_i \left(score(i) \cdot weight(i)\right) \tag{1}$$

Table 3 shows an overview of the trade-off analysis of all the subsystems.

The performed trade-off analysis is a tool that gives broad information about the technologies under study, but it is not a perfect representation of them. For this reason, a technology cannot be discarded if the difference in score with the highest rated ones is small. Moreover, in the analysis of the full system, the interactions between consecutive subsystems must be taken into account: two apparently ideal devices cannot be part of the full system if the interaction between them is poor or even impossible. In addition, and particularly for the present study, if there are no ISRU components in the system or if the system cannot provide the required power, it will be discarded.

This analysis includes several criteria that take logistics into account (transport, cost, maintenance, supplies, etc.), but a few less for efficiency and power. Therefore, it could be slightly biased towards simple designs that may prove to be inefficient when the full system is considered in the simulation work.

Attending only to the scores and selecting the highest rated component for each subsystem, the following combination of technologies is in principle the most recommendable:

Linear Fresnel reflectors → Direct illumination → Molten regolith → Pumped fluid loops → Stirling engine → Pumped fluid loop → Radiator in eternal darkness

For Heat transfer 2 and 3 subsystems, the second best option (pumped fluid) has been chosen because the direct illumination only makes sense for the first section.

Linear Fresnel reflectors seem to be a good choice for the solar energy collection for the same reason that solar panels were chosen for the International Space Station: even though their collecting power is lower than some of the alternatives, the simplicity of operation and repairs compensate the disadvantages.

Direct illumination is compatible with Linear Fresnel Reflectors, but not optimal, because it focuses the light in a line instead of a point and the temperatures obtained are lower that they could be. However, direct illumination is not compatible with the molten regolith storage: even the best concentrators on Earth can barely provide enough temperature to sinter the surface of regolith. Therefore, it is not possible to melt the regolith by means of this solar concentrator.

The heat engine and the cold part of the system seem to match well, provided that the fluid used in the cold side can stand the lunar night temperature.

After analyzing the results, we can suggest some other combinations that use components with high scores with a correct interface between each other. Using Linear Fresnel reflectors is a good choice, but they would interface better with pumped fluid loops, which can bring a constant supply of cold liquid to the focal line and carry the heat away. Still, the temperatures provided by the collector will probably not be enough to melt regolith, so the second-best solution (sintered regolith with fins) is suggested. Although an effective procedure for sintering large blocks of regolith has not yet been developed, the progress in the area is very promising and one can expect that by the time the settlement will be built the enhanced thermal properties of a sintered regolith block will outweigh the troubles of building one.

The Stirling engine, a simple heat engine with space heritage and good performance, appears to be a good solution for energy conversion. If passive generators improve enough in time, they will probably become the preferred solution.

Finally, a radiator in eternal darkness is clearly the best option for heat rejection, but because the list of locations where it can be used is so small, it is better to consider the second best option: a shielded radiator, created with in-situ materials if possible.

Therefore, a more recommendable choice of components is:

Linear Fresnel reflectors → Pumped fluid loop → Sintered regolith block with metal fins → Pumped fluid loop → Stirling engine → Pumped fluid loop → Shielded radiators (ISRU)

An estimation of the required mirror and radiator area for this configuration and a 100 kWe production can be seen in Figure 4.

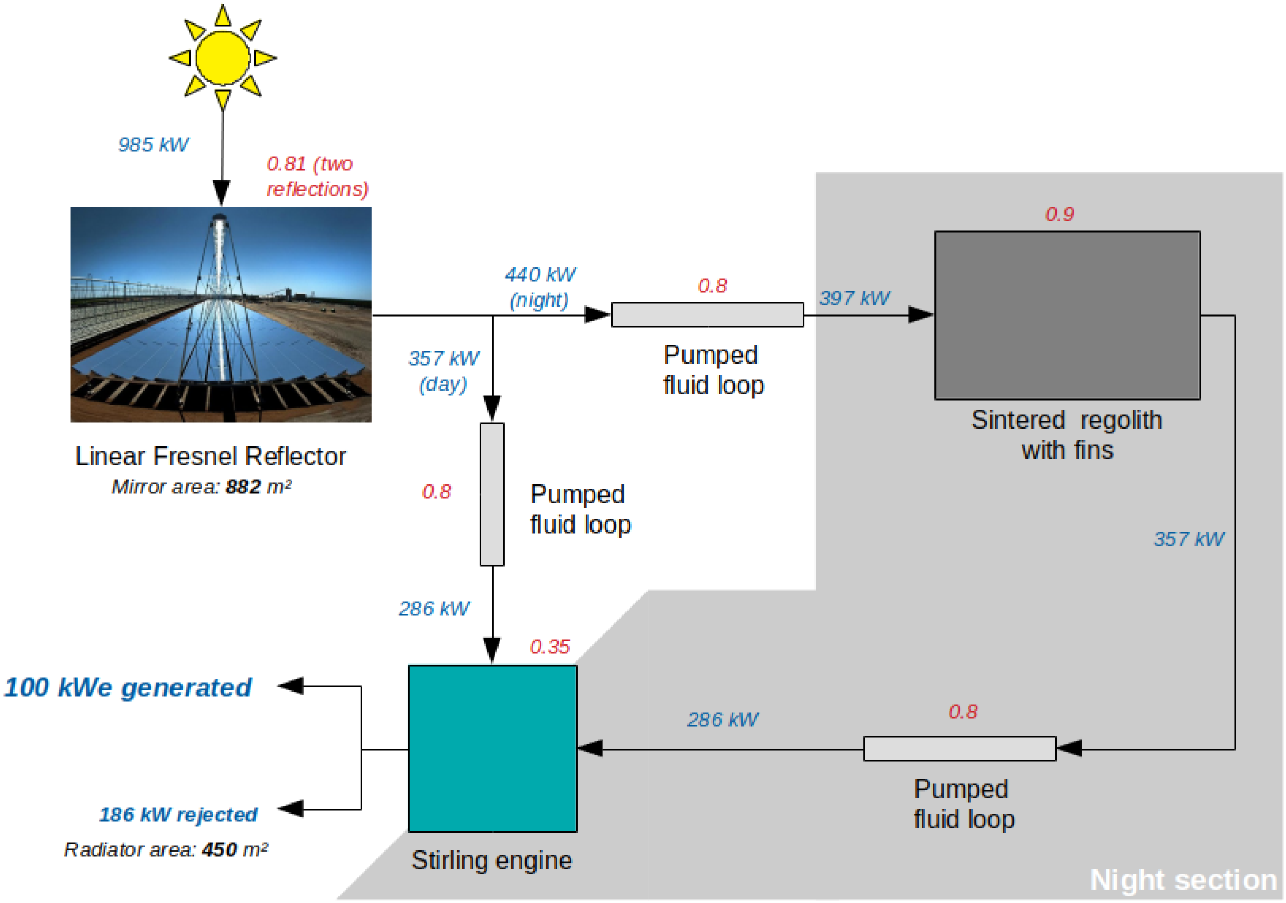

Figure 4: Mirror and Radiator area estimation for the recommended configuration and a 100 kWe production.

		Linear Fresnel reflectors	Central receiver	Parabolic troughs	Parabolic dish	Off-axis solar concentrator	Fresnel lens		Direct illumination	Metal bars	Pumped fluid loop	Optical waveguide	Heat pipe	Loop heat pipe		Loose regolith	Sintered regolith	Molten regolith	Loose regolith w/ metal fins	Sintered regolith w/ metal fins	Fuel cell with ISRU hydrogen		Stirling	Brayton	Rankine	Thermoelectric	Thermoacoustic	Thermionic	Thermophotovoltaic		Radiator (aluminum)	Shielded radiator	Radiator in eternal darkness	Loose regolith
Evaluation criteria	Weight	**Solar collection**						Weight	**Heat transport**						Weight	**Energy storage**						Weight	**Heat-to-electricity conversion**							Weight	**Heat rejection**			
Transport from Earth	3	3	3	3	3	2	1	3	n/a	2	4	3	2	2	2	5	4	4	4	4	2	4	3	2	1	1	3	1	1	2	2	2	2	5
Installation/construction	2	3	2	3	3	4	4	2	5	4	2	2	3	4	2	5	3	3	4	3	4	2	2	2	2	4	2	4	4	2	4	3	2	4
Operation and maintenance	2	4	2	4	2	3	3	2	5	4	2	2	4	4	2	5	5	3	5	5	4	2	4	3	1	5	4	5	5	2	5	5	5	5
ISRU	5	0	0	0	0	0	0	5	n/a	0	0	0	0	0	5	5	4	4	4	4	2	5	0	0	0	0	0	0	0	5	0	3	3	5
Scalability	3	4	4	3	3	4	3	2	n/a	4	3	4	1	1	3	5	3	3	4	3	3	3	3	3	3	5	3	5	5	3	4	4	4	5
Lifespan	3	4	4	4	3	4	4	2	5	5	4	5	5	5	2	5	5	?	5	5	4	3	4	3	3	4	3	?	?	3	5	5	5	5
End of life	1	2	2	2	2	2	2	1	n/a	4	2	2	2	2	1	4	4	4	4	4	2	1	2	2	2	2	2	2	2	1	3	3	3	5
Cost	2	3	2	3	2	4	5	2	5	4	2	2	3	3	2	5	4	4	4	4	3	2	2	2	1	3	2	3	2	2	4	3	4	5
TRL	1	4	4	4	4	4	4	1	n/a	4	4	2	4	2	1	3	3	3	3	3	3	1	4	4	2	5	1	5	2	1	5	5	5	3
Technology maturity on Earth	2	5	5	5	5	5	5	2	n/a	5	4	4	4	2	1	5	3	2	5	3	5	2	4	4	4	3	1	2	2	2	5	5	5	5
Operational in high temperatures (up to 1000K)	5	5	5	5	5	5	5	5	n/a	5	5	3	3	3	5	5	5	5	5	5	n/a	5	5	5	5	5	5	5	5	-	n/a	n/a	n/a	n/a
Concentration ratio	2	2	4	3	5	2	4	-	n/a	n/a	n/a	n/a	n/a	n/a	-	n/a	n/a	n/a	n/a	n/a	n/a	5	3	4	5	3	3	3	1	-	n/a	n/a	n/a	n/a
Performance/Efficiency	-	n/a	n/a	n/a	n/a	n/a	n/a	5	5	1	4	4	2	2	-	n/a	n/a	n/a	n/a	n/a	n/a	5	5	4	3	1	3	2	3	4	3	4	5	1
Volumetric heat capacity	-	n/a	n/a	n/a	n/a	n/a	n/a	-	n/a	n/a	n/a	n/a	n/a	n/a	5	1	3	4	1	3	n/a	-	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4	3	3	3	1
Thermal conductivity	-	n/a	n/a	n/a	n/a	n/a	n/a	-	n/a	n/a	n/a	n/a	n/a	n/a	5	1	3	4	2	4	n/a	-	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4	4	4	4	1
Specific power	-	n/a	n/a	n/a	n/a	n/a	n/a	-	n/a	n/a	n/a	n/a	n/a	n/a	-	n/a	n/a	n/a	n/a	n/a	n/a	4	2	4	5	1	1	1	1	-	n/a	n/a	n/a	n/a
Operational in low temperatures (lunar night)	-	n/a	n/a	n/a	n/a	n/a	n/a	-	n/a	n/a	n/a	n/a	n/a	n/a	-	n/a	n/a	n/a	n/a	n/a	n/a	-	n/a	n/a	n/a	n/a	n/a	n/a	n/a	5	5	5	5	5
SCORE		98	94	97	92	97	97		156	96	97	86	77	73		137	136	142	128	141	82		136	135	127	117	110	116	106		140	155	159	148

Table 3: Overview of the trade-off analysis of all the subsystem

5 - Model of study

Figure 5 shows a snapshot of the model schematics developed in EcosimPro.

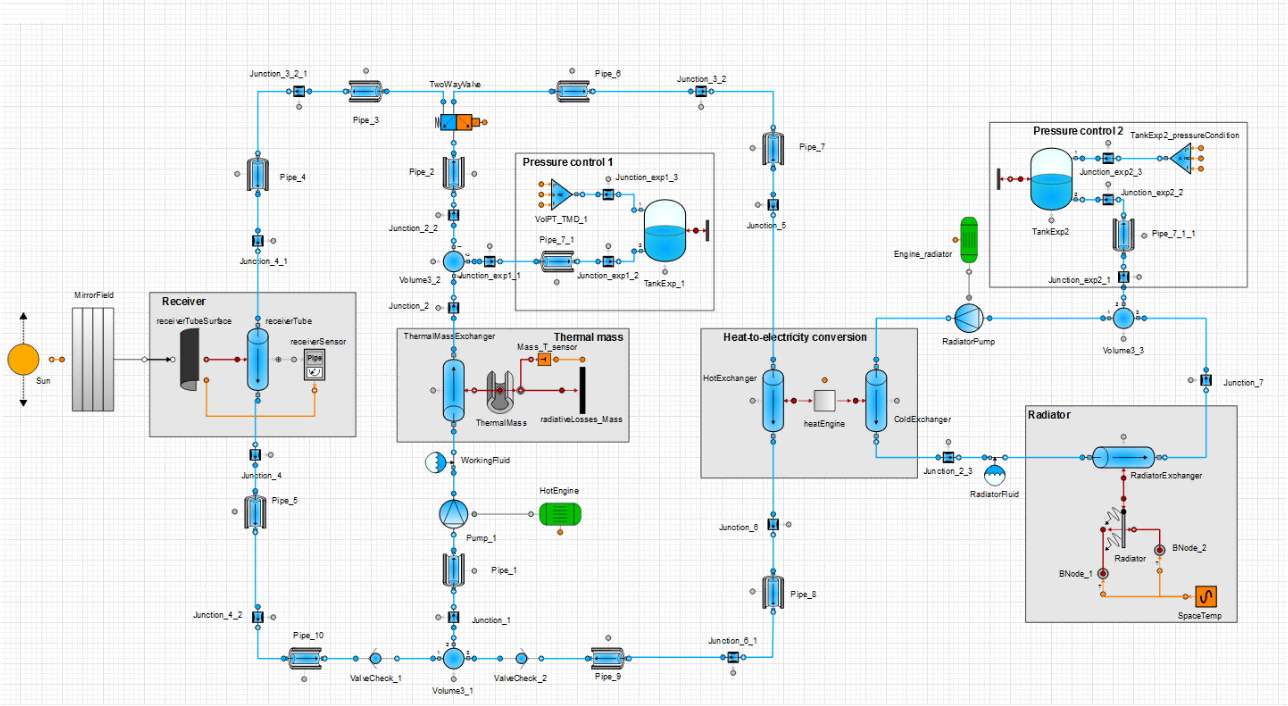

Figure 5: Schematics of the Ecosimpro model.

Figure 6 shows a simplified diagram of the system main components and connections, and of the direction of the flows.

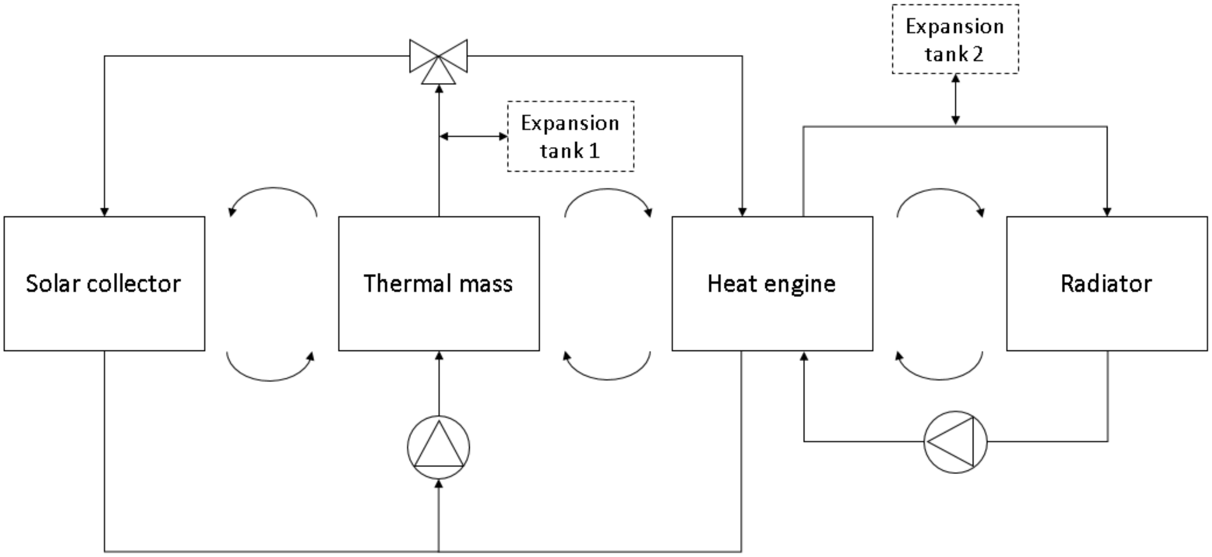

Figure 6: Simplified diagram of the simulator.

The system consists of three fluid loops. The collection loop runs during the lunar day, transporting heat from the sunlight collector to the thermal mass and rising its temperature. The discharge loop is active during the lunar night, transporting heat from the thermal mass to the hot side of the heat engine. The radiator loop runs when the heat engine is running, transporting heat between the cold side of the heat engine and the radiator.

In addition to the main subsystems, the system includes some extra components: valves, pumps, and two expansion tanks to control pressure.

Each subsystem has been independently modelled, analyzed and validated. Once all subsystems have been modelled and validated, simulations of the full system can be carried out. Results on the behavior of the different subsystems consistent with what is expected have been obtained in the simulations of the full system.

6 - Power

The specific power is calculated in two scenarios. In the first one, the characteristics of the components corresponding to simulations to generate 100 We are considered. In the second scenario, an estimation of the specific power for a larger system that can generate 10 kWe has been carried out.

The estimation of the components mass for the 100 We scenario are:

- Mirror field: The 10 m^2 mirror field, at an estimated density of 20 $kg \cdot m^{-2}$, weights 200 kg.
- Tubing: The configuration should be as compact as possible, both for reducing the mass of the system, and for minimizing the heat losses in transport. We estimate a minimum of 50 m, that should stand up to 1 MPa, and be compatible with liquid sodium. One could consider the Hastelloy X alloy, with a density of 8220 $kg \cdot m^{-3}$, and a thickness of 1.25 mm. With the dimensions of the simulation (diameter Di = 0.01 m), the volume of material would be 4.42e-5 m^3/m, corresponding to 18.16 kg.
- The pipes would hold approximately 7.85e-5 m^3/m (cubic meters of fluid per meter of tubing). With 50 m of tubing, and a liquid sodium density of 927 $kg \cdot m^{-3}$ = 3.63 kg. This is reusable, but mandatory, so there should be plenty more. We can consider a margin of 20 times more, which gives a final result of 72.6 kg. Since ethanol will be used in the radiator, and being its density lower than the liquid sodium density, the final mass considered here is over estimated.
- Pumps and engine pumps: We estimate 200 kg.
- Pressure control tanks: They are, in principle, simple and small components. We estimate 100 kg for both tanks.
- Stirling engine: an engine generating 7 kWe weights 125 kg. For our goal or 10 kWe we estimate, at least, 200 kg.
- Radiator: we have used the size of one of the radiators from the ISS of density 8.51 kg/m^2 [11]. Hence, the 78 m^2 result in 663.78 kg.
- Thermal mass (one regolith cylinder): $2.36 \cdot 10^4$ kg.

The total mass is 25054.54 kg with the ISRU thermal mass, and 1454.54 kg without it. Therefore, for a power generation of 100 We, the specific power of the total system would be $0.40 \cdot 10^{-2}$ $W \cdot kg^{-1}$. Leaving the thermal mass out and considering only the mass required to be brought from Earth, the value goes up to 0.069 $W \cdot kg^{-1}$.

We can also estimate from this system the specific power of a full-size system able to produce 10 kWe. In this case, the number of regolith tubes will have to be multiplied by a maximum of 100, hence the final mass of sintered regolith will be of $2.36 \cdot 10^6$ kg.

The mirror field is now bigger. We estimate that a mirror field of 500 m^2 would be required, in order to have a receiver area of 0.5 m wide through which multiple receiver tubes can pass. Again with the previous value for density of 20 $kg \cdot m^{-2}$, the new mirror field would weigh 10^4 kg.

The mass of HTF would also have to be multiplied by 100, giving 7260 kg. In fact, this is an overestimation as regards to the radiator loop since it would not have to be replicated 100 times.

In the thermal mass, the tubing circuit will be subdivided in 100 small tubes, hence the10 m of tubing of the small system will be multiplied by a hundred for the large system. In the rest of the circuit, the tubes will need to hold a 100 times bigger flow. However, this does not represent a hundred times increase in the weight of the tubes because the surface of the tube scales proportionally with the radius, and the flowrate with the square of the radius. Instead, we estimate that the increase in piping material will be around 10 times. The final calculation is 100 tubes like the ones in the previous section, and a length of 10 m, plus 40 m of tubing with 10 times the radius, resulting in a mass of approximately 495 kg.

The pressure control tanks, pumps and pump engines, Stirling engine, and radiator do not need to be scaled up, as they were already over-dimensioned.

The total mass would be $2.38 \cdot 10^6$ kg with the ISRU mass, and 18918.78 kg without it. The final specific power would be $4.2 \cdot 10^{-3}$ $W \cdot kg^{-1}$ with the thermal mass, and 0.53 $W \cdot kg^{-1}$ without it.

If in the future there was a chance to make mirrors out of ISRU materials, or by reusing materials from visiting spacecraft in order to save weight, the required mass could be significantly reduced.

An overview of these results is shown in Table 4.

Power (We)	Total mass (kg)	Total mass, no ISRU (kg)	Specific power, total system ($W \cdot kg^{-1}$)	Specific power, no ISRU ($W \cdot kg^{-1}$)
100	$2.51 \cdot 10^4$	$1.45 \cdot 10^3$	$0.40 \cdot 10^{-2}$	0.069
10^4	$2.38 \cdot 10^6$	$1.89 \cdot 10^4$	$0.42 \cdot 10^{-2}$	0.53

Table 4: Mass and specific power of the different configurations.

These results could be compared to those of the technology that this system aims to beat in this scenario: photovoltaic power plus batteries. As a reference we can use the Li-ion batteries that have been recently installed on the ISS. These batteries are contained in boxes called Orbital Replacement Units (ORUs) that include not only the power cells, but also all the necessary connections, controllers, and safety components. It is expected that batteries would be delivered to the Moon in a similar configuration, in containers of specified size and connections, that are protected from launch stresses and vacuum environment, and are easy to replace when necessary.

A difference that one can think of between the requirements of the orbit and the lunar surface may be in the amount of protection from micrometeoroids. The battery ORUs could be protected by the lunar surface, or by 3D printed structures. In order to account for that, we can subtract some weight from the calculations.

Each Li-ion battery ORU weighs 197.3 kg [12], that we can reduce to 150 kg in order to account for the removal of micrometeoroid protection. Each ORU contains 30 cells connected in series, each with a nominal capacity of 148 Ah and a nominal voltage of 3.7 V. This gives an energy of 548 Wh per cell, or 16.44 kWh for a complete ORU.

In order to hold enough energy for a lunar night (3.54e6 Wh), it would be necessary to have 215 ORUs, that would weigh 32250 kg. This value is considerably larger than the mass of the ISRU-based system excluding the thermal mass (18918.78 kg). In addition, the mass of the additional components required (connections, controllers, and solar panels) has not been taken into account in the calculation.

In conclusion, the estimation of the mass required to supply 10 kWe by the ISRU-based LIESEG system shows that this system is very competitive in comparison to a system composed of photovoltaic panels and batteries.

7 - Bibliography

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