Lunar ISRU Energy Storage and Electricity Generation

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Abstract

Fifty years after the first human step on the Moon, many challenges for its exploration have yet to be overcome. Among them, the survival of the crew and/or lunar assets during the lunar night is mandatory for long duration missions. The environmental conditions of the lunar surface and its day-night cycle, with long periods of darkness, make the provision of energy a critical challenge. Several approaches have recently been considered to store and provide energy in the surface of the Moon by means of ISRU (In-Situ Resource Utilisation). We present a trade-off analysis of the options identified for an ISRU-based system to store heat and generate electricity for lunar missions with both robotic and human activities. A critical review of the energy requirements for a mission scenario consisting of long duration stays on the lunar surface has been carried out. Technologies potentially suitable for system components have been identified. These technologies are related to solar energy collection, heat transport, heat storage, heat-to-electricity conversion, and heat rejection. The outcome of the trade-off analysis provides a selection of the most suitable technologies to use in an ISRU-based heat storage and electricity generation system.

Keywords:
Moon, ISRU.

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Preprint submitted to Acta Astronautica *December 4, 2019*

1. Introduction

Humankind tested its capacity to survive on the surface of the Moon for short periods of time in the Apollo missions almost 50 years ago. Since then, robotic missions to the Moon have spent some days and a few nights on 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. Such system would ideally be based on ISRU, which would reduce the payload mass required to be brought from Earth, and allow lunar habitats a certain level of independence.

The harsh lunar environment presents unique challenges for human exploration, such as the long periods of darkness on almost all latitudes, hard vacuum (approximately 10^{-11} torr), severe temperature day-night cycling, no atmospheric protection from meteor impacts, no magnetic protection against hard radiation, little amount of water, and lunar dust.

Daytime in the equator of the Moon is about 14.77 Earth's days long, half of its synodic period. This makes the conventional method for power generation in space (solar panels plus batteries) inconvenient because a large amount of batteries is required. Moving away from the equator would only slightly modify these conditions, because the small axial tilt of the Moon (1.54° to the ecliptic, 6.68° to its orbital plane) results in minimal seasonal variations. Certain features of the Moon offer special illumination conditions, such as lava tubes, peaks of eternal light, and craters of eternal darkness. In these regions there is a permanent or almost permanent illumination or shadow, characteristics that can be exploited for energy generation or excess power dissipation.

The surface of the Moon, devoid of an atmosphere, experiences very large temperature oscillations. Simulations performed by Vasavada et al. [1] show temperatures of 400 K during daytime and below 120 K during nighttime at the equator, with a decrease in the maximum temperature with latitude. Moreover, 0.5 m below the surface at the equator the temperature remains nearly constant over time at approximately 250 K. Therefore, a few tens of centimeters of lunar regolith could effectively isolate humans and equipment from the temperature variations above.

The lack of atmosphere has conditioned the surface of the Moon, which is covered by lunar regolith, a mantle of pulverized rock resulting from eons of bombardment by interplanetary matter of all sizes and energies. The density of the surface layer changes with depth and ranges from 1300 to 1900 kg/m^3 [2], and the density of the rocks underneath ranges from 2500 to 3400 kg/m^3 [3], both of them depending on the location. The composition of the soil is slightly different in the highlands and in the maria, the two distinct regions of the Moon. The regolith and rock samples brought to Earth in the Apollo missions are limited in number, and represent a small sample of the Moon's diverse geology. All measurements and characterization of materials since the seventies have been taken from orbit, by small mobile laboratories on board of surface rovers, or have been performed on terrestrial rocks considered sufficiently similar to those on the Moon. Table 1 shows the thermophysical properties of the regolith and rock layers. Raw regolith can in principle be considered to store sensible heat in a power generation system. The main advantages of raw regolith are ISRU, large availability, and large operating temperature range. The main disadvantages for the use of raw regolith as a thermal energy storage material are its low thermal conductivity, the need of a heat transfer fluid to transfer heat effectively, and the dispersed particle size, which may require compaction.

	Regolith	Rock
Density (kg m^{-3})	1700 [2]	2900 [3]
Thermal conductivity (Wm^{-1}K^{-1})	$7.0 \cdot 10^{-3}$ [4]	0.66
Thermal diffusivity (m^2 s^{-1})	$6.86 \cdot 10^{-3}$	$3.5 \cdot 10^{-7}$ [5]
Specific heat capacity (J kg^{-1} K^{-1})	600 [6]	650 [6]

Table 1: Properties of lunar regolith and rock.

Processing raw regolith by sintering could enhance its thermal properties so that the final product becomes more adequate for a thermal energy storage system [7, 8]. In a sintering process, a solid mass of material is compacted and formed by applying pressure or heat at temperatures below the melting point. The most likely regolith sintering methods to be used on the Moon are based on microwaves, concentrated solar energy, or laser. In microwave sintering, the surface of powdered regolith is treated with specific microwave frequencies, with the objective of coupling the microwave energy with some of the constituents of regolith and melting them while other components remain solid. This method controls the elements that couple with the microwave energy, the depth of penetration, and the properties of the final product, by tuning the microwaves. Lunar regolith could be melted down to 0.5 meters and used to produce several types of structural materials, like bricks or solid pavement [9]. Regolith sintering is also possible by concentrating solar power on top of the material [10]. This method can achieve very high temperatures without the need of an electrical power source. However, processing is limited to daytime and requires a tracking system to move the focal point. Moreover, sintering with this method only reaches depths of the orders of millimeters. Laser sintering allows a better control than the previous methods, both in intensity of the light and geometrical accuracy of the beam. Laser can also produce much higher temperatures than any other method, and achieve melting instead of sintering. While a sintered piece keeps some of the original grains intact, held together by other grains that have melted, selective laser melting can join all the components into an amorphous structure [11].

Thermal wadis are engineered solar energy storage systems that use modified regolith as a thermal storage mass [7]. Wadis can store heat during the lunar day, and supply heat during the lunar night to rovers. They are good candidates to provide the required thermal energy for the survival of rovers and other equipment during periods of darkness. However, temperatures reached in a wadi heated with a reflector and with a heat-loss protection are not high enough to run a heat engine efficiently during the lunar night [8]. Therefore, alternative systems are required for missions with high power requirements.

We present a comparative analysis of ISRU-based power systems potentially suitable for lunar habitats. A review of power requirements for different lunar habitats is presented in Section 2. Section 3 contains a trade-off analysis of several for the subsystems and the full energy storage and electricity generation system. Conclusions are presented in section 5.

2. Power requirements for a lunar habitat

Fig. 1 shows the relation between the mission objectives, energy requirements and power generation and storage systems for missions on 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.

Since the last Apollo mission ended, the next manned mission to the Moon has been long awaited but has never happened. However, a trail of

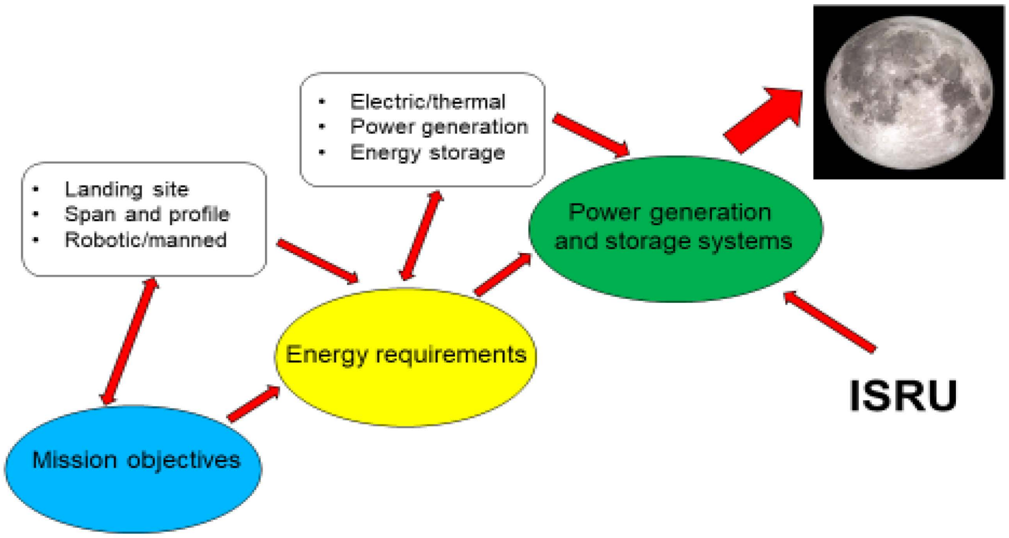

Figure 1: Relationship between mission objectives, energy requirements and power generation and storage systems for missions in the Moon.

scientific and technical studies have been carried out with the aim at envisioning how to build a habitat, how to power it, and the power requirements. An analysis of these studies allows us to provide here an estimation of the power requirements for future lunar habitats.

Petri et al. [12] proposed a settlement built in three progressive phases. The first one consists of an outpost with a power consumption of 25 kWe (daytime, D) and 12 kWe (nighttime, N) followed by an expansion reaching 80 kWe (D) and 50 kWe (N). The difference in day and night power is explained by the fact that the power generation capabilities are reduced at night. The third phase includes a larger habitat and the construction of ISRU facilities that would raise the consumption to 180 kWe (D) and 150 kWe (N). Photovoltaic cells (PV) are proposed during the day and regenerative fuel cells (RFC) during the night for the first phase, and a nuclear power plant and a pilot lunar liquid oxygen plant for later stages. Cataldo and Bozek [13] described a 45-days mission to a lunar outpost that includes a preparation phase of the settlement using robots. Power consumption is estimated to be 12 kWe (D) and 11 kWe (N). Mason et al. [14] analyzed the feasibility of fission nuclear power sources on the Moon. Although nuclear power is currently not being considered for manned missions, their estimations on power consumption are worthy for our analysis. The authors suggest installing a 5-year lifespan 30 kWe plant, and replacing it later on by two new plants producing 40 kWe each. Khan et al. [15] studied a power supply and storage system for a polar lunar base, consisting of PV and RFC, and discussed the use of batteries. A consumption of 81 kWe is estimated without taking into account night conditions. Landis [16] reviewed a large number of scenarios to provide power to a lunar base during the night. Power requirements of 100 kWe (D) and 50 kWe (N) are estimated. Balint [17] analyzed several power generation systems for the Moon and Mars. The lunar settlement requirements are expected to gradually grow from a few kWe to 100 kWe. Later, ISRU facilities will add between 30 kWe and 50 kWe.

We consider the Apollo program [18] as a special case in the power requirements analysis. Six lunar modules successfully reached the surface of the Moon, and stayed there for durations between 21 and 72 hours. The lunar modules were initially designed to be powered by a combination of fuel cells and batteries. Three fuel cells could provide between 400 W and 1420 W each at 31 to 27 VDC. Therefore, the estimated theoretical maximum available power for the lander was 4.2 kWe, without taking batteries into account. Nevertheless, the fuel cells were removed from the power design shortly before the missions. The final version of the lunar module was powered by seven batteries (six initially, plus one that was added after the Apollo 13 accident). Five 400 Ah batteries where located in the descent section and two 300 Ah batteries were in the ascent section. They all provided 28 VDC to the bus. Although the power consumption of the lunar module is not available, an estimation can be performed. Assuming a mission duration of 75 hours and a constant power consumption during this time, the batteries could provide a maximum of 970 W to the module. Consumption during EVAs and resting periods of the astronauts would be lower, and higher during ascent and descent operations.

Table 2 shows a summary of the power consumption of lunar outpost missions at different stages. The power requirements in surface outposts and bases are expected to range from 25 kWe to a few hundreds of kWe during the early build-up phases. As the base becomes fully operational with in-situ resource production and closed-loop life support, power requirements could approach 1 MW. The night power requirements considered in this work are of the order of 10 kWe (stage 1).

	Power consumption (kWe) and sources					
Study	1st stage	2nd stage	Early source	3rd stage	Next stages	Later source
Petri et al. [12]	25(D) 12(N)	80(D) 50(N)	PV/RFC	180(D) 150(N)	200+	PV/RFC + Nuclear
Cataldo and Bozek [13]	12(D) 11(N)	-	-	-	-	-
Mason et al. [14]	30	80	Nuclear	-	-	Nuclear
Khan et al. [15]	-	81(D)	PV/RFC		-	Nuclear
Landis [16]	-	100(D) 50(N)	Undefined	100+	-	-
Balint [17]	10-100		PV/RTG	100+	-	Others
Apollo [18]	0.97		Batteries	-	-	-

Table 2: Summary of power consumption of lunar habitats

3. Heat storage and electricity generation

3.1. System architecture

Fig. 2 shows the proposed model for the energy storage and electricity generation system based on the work by Climent et al. [8]. The energy collected by the Solar Collector is transported to a Energy storage subsystem and, when it is needed, to a Heat-to-electricity conversion unit. The cold side of this unit is connected to the Heat rejection unit, so it can stay at the appropriate temperature. The dotted line in Fig. 2 shows the option of a direct energy transfer to the converter without storing it, which accounts for the direct generation of electricity from sunlight during daytime.

3.2. Description of suitable technologies

3.2.1. Solar collection

The solar collectors selected for this study can be divided in three groups. The first one would be composed of the parabolic dish (PD) and central receiver (CR): point focus technologies designed for maximum concentration of sunlight. In PD plants sunlight is directed into their focal points using paraboloidal mirrors, achieving maximum theoretical concentration. The sun is tracked in two axes by pointing the center of the mirror to the Sun throughout the day. CR plants also obtain high sunlight concentration ratios. They consist of a central receiver tower, and a set of two-axis-tracking heliostats that focus the sunlight onto the central receiver.

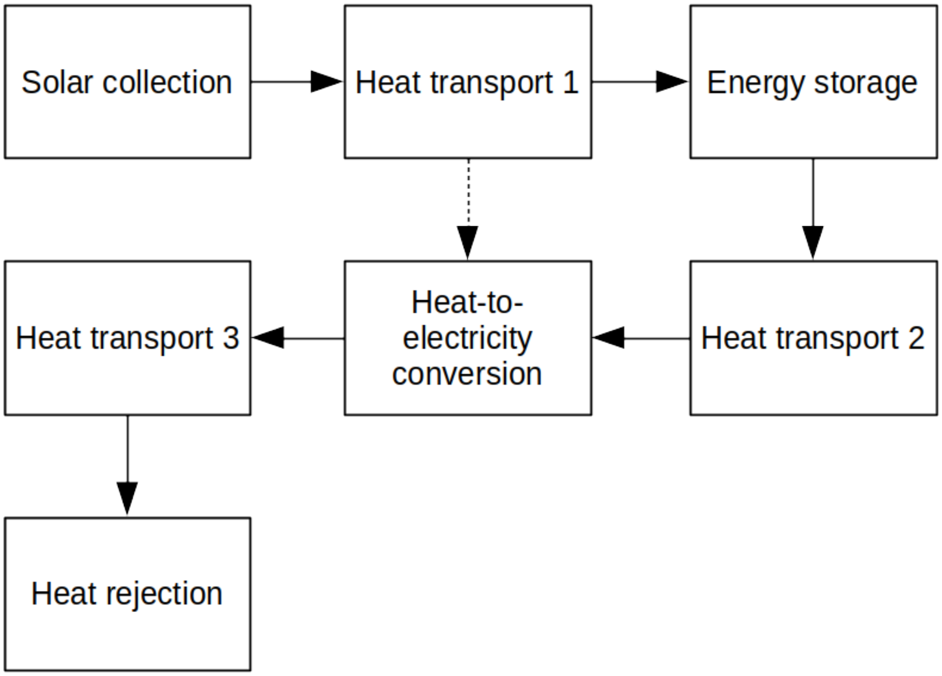

Figure 2: Model of the energy storage and electricity generation system.

A second category of collectors sacrifice concentration power in exchange for simplicity. Both linear Fresnel reflectors (LFR) and parabolic troughs (PT) concentrate sunlight in a line instead of a point, providing less efficiency, but requiring a simpler device. LFR consists of a field of flat mirrors configured to focus the light similarly to a huge parabolic cylinder mirror. PT use sets of parabolic cylinder mirrors, which results in a better concentrating power than in LFR.

We consider a third group of concentrators, which are characterized by their simplicity to be built and manipulated. Off-axis concentrators consist of a static parabolic reflector and one or more sun-tracking flat reflectors that guide sunlight into it. Fresnel lenses focus parallel light rays into a point similarly to a plano-convex lens, but with reduced mass.

3.2.2. Heat transport

There are several different ways of transporting heat around the system.

The direct illumination method consists of simply transmiting light from the collector to the thermal mass through the vacuum, in the form of visible light. This technology is only applicable for the first heat transport subsystem, just after the collector.

Another option is to use a pumped fluid loop, in which a heat transfer fluid is pumped around a closed circuit, exchanging heat with cold and hot sources, and transporting the energy.

Heat pipes are a passive alternative to the pumped fluid loop. They are sealed systems that contain a heat transfer fluid, an evacuated chamber, and a porous surface, and are specifically designed so at certain temperature differences the fluid evaporates on one side of the pipe and condenses on the other.

If transport by conduction is good enough, there is the option of simply connecting the subsystems with metal bars, made of a material with appropriate thermal characteristics.

Finally, it is possible to adapt the system to use optical waveguides, fiber optics in this case, to transport sunlight without transforming it into heat first.

3.2.3. Energy storage

All the considered technologies store energy in form of heat except the fuel cells with ISRU hydrogen and oxygen, for which the system architecture in Fig. 2 would change.

The energy storage subsystem is the perfect candidate for satisfying the ISRU criterion of the power system. Raw or processed regolith can be converted into a heat storage device. Regolith is a costless component which is largely available.

Loose regolith means using raw lunar regolith as the heat storage, surrounding a heat-exchanging structure, which could consist on pipes buried under the lunar surface. Sintering of regolith can enhance the thermal properties of regolith while keeping its advantages. The use of metal fins in contact with the pipes would increase conductivity even further.

Additionally, the regolith could be used as an energy storage in molten state, keeping it as latent heat after the phase change instead of sensible heat.

The last option considered is the use of fuel cells, obtaining oxygen and hydrogen from local water. However, even if the presence of water on the

Moon has been demonstrated, it is unclear where it is located and how much there is.

The use of fuel cells would imply changes in the power system architecture, probably generating electrical energy directly from the concentrated solar power or photovoltaic panels, and using it to run an electrolyzer.

Storage of energy in lunar regolith of any kind has never been tested, neither on Earth nor on the Moon. Heat has been stored in concrete at DLR [19] and at EnergyNest [20], although a generator has never ran for the time required in our application.

3.2.4. Heat-to-electricity conversion

Four heat engines have been considered in the analysis: Stirling, Brayton, Rankine, and thermoacoustic. Thermoacoustic engines fall down in the ranking because, although they are very promising, they are less mature than the other heat engine technologies. The other three technologies (thermionic, thermoelectric, and thermophotovoltaic) are passive converters of thermal gradients into electricity.

3.2.5. Heat rejection

Two main options have been considered for heat rejection: dumping the heat on the surface of the Moon, or into space by means of a radiator. Using the lunar surface as a cold sink is the easiest option, but the same properties of the native regolith that make it a poor choice for a thermal mass, make it a bad option for this job, as the transmission rate of the heat into the ground would be very small, and the surrounding area would start to heat up.

A better option would be to use a radiator, a space-proven device of simple operation. There trade-off analysis must find the best way of using them: they could be installed on the base, covered by a solar shield, or in a permanently shadowed location.

4. Trade-off analysis

4.1. Trade-off methodology

A trade-off analysis of the identified technological options has been carried out for each subsystem. 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 for each subsystem, and technologies and components are scored for each criterion.

Quantitative analysis has been used whenever possible. In those cases in which data was available (specific power of the electricity generators, concentration ratio of collectors, TRL values, etc.) the technologies were arranged according to the value in question and then ranked accordingly. However, most of the criteria are subjective and a value cannot be assigned to them, so a qualitative analysis has been performed for them.

- **Transport from Earth:** difficulty and cost of transport, including mass, storage volume, and ability to withstand the conditions of a rocket launch.
- **Installation and construction:** complexity of construction and installation, 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 capabilities of the subsystem.
- **Lifespan:** expected duration of the component before repairs or replacement.
- **End of life:** usefulness of the components after decommission, or possible hazards caused by the remains.
- **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 criteria have only been considered for some of the subsystems:

- **Concentration ratio:** ratio between the collector's aperture and the surface area of the receiver. Its physical meaning is the factor by which the solar incident flux is optically enhanced on the receiving surface. Applicable to solar energy collection.

- **Performance efficiency:** power output to power input ratio. Applicable to heat transport, heat-to-electricity conversion, and heat rejection.

- **Power, Specific power:** total power generated and power-to-mass ratio. Applicable to heat-to-electricity conversion.

- **Volumetric heat capacity, thermal conductivity:** thermal properties. Applicable to energy storage (thermal masses) and heat rejection.

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 by means of:

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

where i refers to each considered technology. Eq. 1 is meant to give a fair score to those technologies that are so different to their equivalents that do not fit in the trade-off, such as direct illumination of thermal masses. If only a few criteria are applicable to a technology, but their scores are high in categories with high weight, the resulting score is very high.

4.2. Solar collection

Table 3 shows the outcome of the trade-off analysis of the technologies in the solar energy collection subsystem.

In the trade-off analysis, technologies sharing a common collector (*e.g.* LFR) have been considered more scalable than those requiring new units to be built (*e.g.* PT). All collectors score zero points in ISRU since the production of mirrors and glass from regolith is being investigated, but has never been tested in lunar conditions and one can assume that it will not be available in the first settlements.

The outcome of the trade-off gives the highest score to the linear Fresnel reflectors, closely followed by parabolic troughs, off-axis concentrators and Fresnel lenses. The technologies that are penalized for their complexity are

		Linear fresnel	Parabolic trough	Off-axis concentrator	Fresnel lens	Centrar receiver	Parabolic dish
Evaluation criteria	**Weight**	**Solar collection**					
Transport from Earth	3	3	3	2	1	3	3
Installation and construction	2	3	3	4	4	2	3
Operation and maintenance	2	4	4	3	3	2	2
ISRU	5	0	0	0	0	0	0
Scalability	3	4	3	4	3	4	3
Lifespan	3	4	4	4	4	4	3
End of life	1	2	2	2	2	2	2
Cost	2	3	3	4	5	2	2
TRL	1	4	4	4	4	4	4
Technology maturity on Earth	2	5	5	5	5	5	5
Operational in high temperatures	5	5	5	5	5	5	5
Concentration ratio	2	2	3	2	4	4	5
	SCORE	98	97	97	97	94	92

Table 3: Trade-off of solar energy collection technologies.

rewarded for their performance, and vice-versa. The selection of a technology will depend on the factor considered to be more important for the mission, and the ability to reach the required temperatures for the thermal mass.

4.3. Heat transport

Table 4 shows the outcome of the trade-off analysis of the technologies in the heat transport subsystem. The architecture of the heat storage and electricity generation system includes the heat transport in three connections of subsystems, and the choice may be different for each of them.

The weight of the *lifespan* criterion is lower than usual, as these technologies are expected to last longer than the mission itself.

The direct illumination method stands out because of its simplicity. Transmitting light from the collector to the thermal mass through the vacuum is

		Direct illumination	Pumped fluid loop	Metal bars	Optical waveguide	Heat pipe	Loop heat pipe
Evaluation criteria	**Weight**	**Heat transport**					
Transport from Earth	3	n/a	4	2	3	2	2
Installation and construction	2	5	2	4	2	3	4
Operation and maintenance	2	5	2	4	2	4	4
ISRU	5	n/a	0	0	0	0	0
Scalability	2	n/a	3	4	4	1	1
Lifespan	2	5	4	5	5	5	5
End of life	1	n/a	2	4	2	2	2
Cost	2	5	2	4	2	3	3
TRL	1	n/a	4	4	2	4	2
Technology maturity on Earth	2	n/a	4	5	4	4	2
Performance/efficiency	5	5	4	1	4	2	2
Operational in high temperatures	5	n/a	5	5	3	3	3
	SCORE	156	97	96	86	77	73

Table 4: Trade-off of heat transport technologies.

simple, low cost, requires no maintenance nor transport of spare parts, and there is no energy lost in conversions. However, this method interfaces poorly with some of the collectors and all the thermal masses, as heating them from the top is not optimal [21]. Moreover, this technology is only applicable for the first heat transport subsystem just after the collector.

A pumped fluid loop is the most versatile option to transport heat. It allows several choices of heat transfer fluids, and fluid speed can be dinamically changed in order to adapt the heat transfer. This technology is well known both on Earth and in space (*e.g.* in the ISS ammonia loop). A main disadvantage is that installation and maintenance may require burying and digging-up pipes and pumps when they are affected by wear and, depending on the transfer fluid, by corrosion.

Metal bars and optical waveguides are two affordable, simple and passive options. Fiber optics can transfer energy in the form of light with very little losses, but they suffer from similar interfacing problems with a thermal mass as the direct illumination.

Heat pipes are passive systems that transport energy as latent heat, greatly improving the transfer rates. They are not effective over large distances and cannot fight against gravity, problems that are overcome by the loop heat pipe design. Both are difficult to upgrade because their geometry is fixed at the moment of construction.

One of the advantages of metal bars, heat pipes and loop heat pipes can become a disadvantage during the lunar night. They transport heat passively from the hot collector to the colder thermal mass during the day, without any need for operation (e.g. pumping). However, this passive nature also implies that when the temperature gradient between the collector and the thermal mass is reversed during the lunar night, these devices will transport heat from the thermal mass to the collector, dissipating it into space. In order to avoid this, controllable thermal bridges should be included. Optical waveguides, while also passive, will not operate backwards.

Aside from the special mention for the direct illumination approach, pumped fluid loop and metal bars are the best scored options. The first one is adequate for all three heat transport subsystems, while the metal bars are best suited for the connection between the heat-to-electricity conversion unit and the heat rejection subsystem.

4.4. Energy storage

Table 5 shows the outcome of the trade-off analysis of the technologies in the energy storage subsystem. All the considered technologies store energy in the form of heat except the fuel cells with ISRU hydrogen, for which the system architecture in Fig. 2 would change.

The *transport from earth* criterion has a lower weight than usual, because all the technologies use local materials, and therefore this criterion is not decisive. *Lifespan* is also decreased as most of them are expected to last longer than the mission themselves. Finally, the *technology maturity* is rated low in this case because storage in lunar regolith is equally unknown in all its forms.

The best option obtained from the trade-off analysis of Energy storage technologies is sintered regolith with metal fins. If including fins inside the sintered block proves to be difficult, the sintered regolith option is almost as

		Sintered regolith w/ fins	Loose regolith	Sintered regolith	Molten regolith	Loose regolith w/ fins	Fuel cell with ISRU hydrogen
Evaluation criteria	**Weight**	**Energy storage**					
Transport from Earth	2	4	5	4	4	4	2
Installation and construction	2	3	5	3	3	4	4
Operation and maintenance	2	5	5	5	3	5	4
ISRU	5	4	5	4	4	4	2
Scalability	3	3	5	3	3	4	3
Lifespan	2	5	5	5	2	5	4
End of life	1	4	4	4	4	4	2
Cost	2	4	5	4	4	4	3
TRL	1	3	3	3	3	3	3
Technology maturity on Earth	1	3	5	3	2	5	5
Operational in high temperatures	5	5	5	5	5	5	n/a
Volumetric heat capacity	5	3	1	3	4	1	n/a
Thermal conductivity	5	4	1	3	4	2	n/a
	SCORE	141	137	136	135	128	82

Table 5: Trade-off of energy storage technologies.

favourable, as are loose regolith and molten regolith, which could be used if their performances are proven to be sufficiently good.

4.5. Heat-to-electricity conversion

Table 6 shows the outcome of the trade-off analysis of the technologies in the heat-to-electricity conversion subsystem.

The *transport from earth* criterion is higher than usual in this trade-off because there is a wide range of sizes and weights of the different components, and their difference should be taken into account.

		Stirling	Brayton	Rankine	Thermoelectric	Thermionic	Thermoacoustic	Thermophotovoltaic
Evaluation criteria	**Weight**	**Heat-to-electricity conversion**						
Transport from Earth	4	3	2	1	1	1	3	1
Installation and construction	2	2	2	2	4	4	2	4
Operation and maintenance	2	4	3	1	5	5	4	5
ISRU	5	0	0	0	0	0	0	0
Scalability	3	3	3	3	5	5	3	5
Lifespan	3	4	3	3	4	3	3	3
End of life	1	2	2	2	2	2	2	2
Cost	2	2	2	1	3	3	2	2
TRL	1	4	4	2	5	5	1	2
Technology maturity on Earth	2	4	4	4	3	2	1	2
Performance/efficiency	5	5	4	3	1	2	3	3
Power	5	3	4	5	3	3	3	1
Specific power	4	2	4	5	1	1	1	1
Operational in high/low temperatures	5	5	5	5	5	5	5	5
	SCORE	136	135	127	117	117	110	107

Table 6: Trade-off of heat-to-electricity conversion technologies.

Stirling, Brayton and Rankine are, in this order, increasingly complex and increasingly efficient. The Rankine engine is the most efficient one thanks to the use of latent heat of the transfer fluid. The efficiency in these engines are one order of magnitude above the other considered technologies. The heat engines are relatively heavy and bulky, and the presence of moving parts and flowing liquids or gases implies that repairs will be necessary at some point of their lifetime. Thermoacoustic engines share most of the advantages of these thermal engines while having no moving parts, but the development of this technology is lagging behing the others.

Except for some related experiments (e.g. Stirling cryocoolers [22]), there is little knowledge about heat engines in space. However, thanks to the lunar gravity, albeit small, their behaviour on the surface of the Moon could be predicted. A main disadvantage of heat engines is that they are not scalable, in the sense that new engines should be brought from Earth in order to expand the system.

The three passive technologies (thermoelectric, thermophotovoltaic, and thermionic) are easy to expand. While each of them transforms energy by means of a different physical phenomenon, they all share several characteristics. They are composed of several small, low cost, passive modules, with very little power per unit, but easy to install and form a big surface covering a thermal mass. Additionally, they have no moving parts, eliminating the need for maintenance and reducing the wear and tear of the materials. Both thermionic and thermoelectric generators have already been successfully used in space, as part of nuclear power systems for satellites and deep space probes. Although these technologies may seem to be ideal choices, their small specific power in the current state of development is a significant disadvantage. The number of devices that need to be brought from Earth is very large even for low power requirements.

Stirling, Brayton, and Rankine engines are the best scored technologies in the trade-off. Similar to the solar collectors, the technology with the best power generation is more complex and vice-versa, their scores ending up being very similar.

4.6. Heat rejection

Table 7 shows the outcome of the trade-off analysis of the technologies in the heat rejection subsystem.

In this case the *transport from earth* criterion is lower than normal, because the three types of radiators are very similar in size, and therefore this parameter is not decisive. The exception is the loose regolith, that would require minimal material to be transported from Earth, but this advantage is not that important compared to the thermal properties.

The use of the Moon as a heat sink is convenient because it lowers the equipment needed, as radiators normally represent a big part of the weight of a thermal system. However, the thermal characteristics of this simple approach make it a bad candidate for heat rejection. The three types of radiators considered mainly differ in their implemented location. It is possible that the radiators could be repurposed from visiting spacecraft, built from the aluminum salvaged from spent their spent stages, or from a metal obtained in-situ.

		Radiator in eternal darkness	Radiator with solar shield	Loose regolith	Radiator
Evaluation criteria	**Weight**	**Heat rejection**			
Transport from Earth	2	2	2	5	2
Installation and construction	2	2	3	4	4
Operation and maintenance	2	5	5	5	5
ISRU	5	3	3	5	0
Scalability	3	4	4	5	4
Lifespan	3	5	5	5	5
End of life	1	3	3	5	3
Cost	2	4	3	5	4
TRL	1	5	5	3	5
Technology maturity on Earth	2	5	5	5	5
Performance/Efficiency	4	5	4	1	3
Operational in low temperatures	5	5	5	5	5
Volumetric heat capacity	4	3	3	1	3
Thermal conductivity	4	4	4	1	4
	SCORE	159	155	148	140

Table 7: Trade-off of heat rejection technologies.

The radiated power is related to the temperature difference between the hot side (the radiator in this case) and the cold sink, that in this case would be the deep space. For this reason, the emitting side of the radiator should be pointing towards the sky, and away from radiating sources such as the surface of the Moon.

The radiators would improve their performance if they were shielded from the Sun: if they are illuminated they would absorb some solar energy that would later have to be re-emitted, although this can be minimised by appropriate choice of surface material and finish. In some cases, a shield could be built in order to shadow the radiator. And if the location allows it, the radiator could also be built in a point of eternal darkness.

All the radiators have a similar cost and are passive (considering that the heat transfer fluid, if any, is part of the third heat transport subsystem). Installation is reasonably easy for radiators, harder for radiators with a solar shield (depending on the nature of the shield), and it may be very challenging inside craters, depending on their characteristics.

The radiator in a crater of eternal darkness gets the highest score in the trade-off. However, since its applicability is limited to certain regions in the poles, the second-best option (radiators with solar shields) is more realistic for a larger number of landing sites.

4.7. Discussion

The 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 connected 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.

More criteria related to logistics matters (such as size, weight, ease of transport, and cost) than to efficiency have been considered. Therefore, the analysis is biased towards simple technologies that may prove to be inefficient when the full system is considered in further simulation and experimental tests.

Attending only to the scores, the following combination of technologies would be the most recommendable:

> Linear Fresnel reflectors →Direct illumination →Sintered regolith with fins →Pumped fluid loops →Stirling engine →Pumped fluid loop →Radiator in eternal darkness

For the second and third heat transfer subsystem, the second best option (pumped fluid) has been chosen, as the direct illumination only makes sense for the first section. Linear Fresnel reflectors are the first choice for the solar energy collection, and they could work together with the direct illumination heat transfer. However, the direct illumination interfaces poorly with a regolith block [21]. The inclusion of metal fins helps with the heat transfer, but the system as a whole would work better with either a different heat transfer method or a different heat storage technology. The heat engine and the cold part of the system can match well provided that the fluid used in the cold side can stand the lunar night temperature.

We estimate that at least 45 kW of thermal energy would be required for the power consumption of 10 kWe defined in section 2. For a lunar night (14.77 earth days), a sintered regolith thermal mass ($k = 2.1\ Wm^{-1}K^{-1}, \rho = 3000\ kgm^{-3}, c_p = 800\ Jkg^{-1}K^{-1}$) would need to be made of at least $2.33 \cdot 10^5\ kg$ of sintered regolith, corresponding to a volume of 77 m^3. As a comparison, a thermal mass made of native regolith, with the properties shown in table 1 (lower density and specific heat capacity), the required volume would be around 183 m^3, more than twice than in the previous case.

Alternative combinations of technologies with good scores and correct interfacing can be suggested. For example, linear Fresnel reflectors would interface better with pumped fluid loops, which can bring a constant supply of cold fluid to the focal line and carry the heat away towards a sintered regolith mass. 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 lunar settlement will be built the enhanced thermal properties of a sintered regolith block will outweigh the troubles of building one. The Stirling engine is the selected technology for energy conversion. Nevertheless, if passive converters, like thermoelectrics, improve in efficiency sufficiently in the coming years, they will probably become the preferred solution. Finally, a radiator in eternal darkness is clearly the best option for heat rejection. However, given the limited number of locations where it can be used, it is more recommendable to consider a radiator with a solar shield, ideally built with in-situ materials. Therefore, the following set of components is proposed for the lunar ISRU energy storage and electricity generation system:

> Linear Fresnel reflectors →Pumped fluid loop →Sintered regolith block with metal fins →Pumped fluid loop →Stirling engine →Pumped fluid loop →Radiator with solar shield

Fig. 3 shows the configuration of the proposed system.

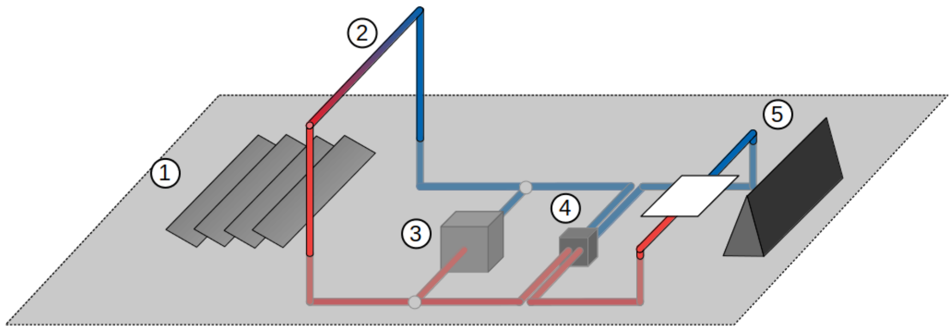

Figure 3: Diagram of the proposed full system. 1: Mirror field, 2: Receiver, 3: Sintered regolith block, 4: Stirling engine, 5: Radiator with solar shield.

5. Conclusions

A trade-off analysis of the technologies and components that could be used in a lunar ISRU-based thermoelectric plant that fulfills the power requirements for settlement missions has been presented. The requirements have been established from the analysis of previous works and missions.

The comparative analysis has been carried out by establishing thresholds for an objective scoring when possible. However, in most of the criteria a qualitative evaluation has been performed. The outcome of the analysis provides a recommended system considering both the scores of the components and the interface between them. Nevertheless, there are still some uncertainties associated to some technologies. In addition, the score of some components are very similar. Therefore, the analysis performed does not define the system that should be built on the Moon but it allows us to discard some technologies and focus on the most promising ones. Further computational and experimental tests of the proposed system are highly recommended.

6. Acknowledgements

We thank Cristina Prieto for fruitful discussions. The European Space Agency is acknowledged for their financial support.

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