Powering Sustainable Moon Exploration: Energy strategies for interoperability and cooperation

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Powering Sustainable Moon Exploration: Energy strategies for interoperability and cooperation

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Abstract

Energy is a mission-critical resource. Developing long-term, large-scale activities on the Moon will require reliable and abundant access to sustainable power supplies. The challenges related to these aspects can be exacerbated by the scarcity of resources such as surface area and sunlight - such as in peaks of eternal light - as well as by the presence of multiple actors with potentially conflicting needs and goals. The aim of the present work is to identify tailored configurations of power generation, distribution and storage solutions with the highest potential to sustainably support the development of strategic lunar locations, such as permanently shadowed regions, far-side smooth terrains and pits. Key drivers in this research are interoperability between different players and compatibility with the peculiar characteristics of the environments under consideration.

State of the art technologies are examined and traded off by adopting multi-criteria decision making tools. Criteria are selected among key technical parameters such as energy density and lifespan, and environment-related performances like resistance to extreme temperatures. Each criteria is weighted differently according to the examined strategic location. A sensitivity analysis is conducted to assess how certain technological advancements in power systems can increase their fitness for the reference applications and regions. The outcome is a set of tailored recommendations on power systems selection and technology developments that can mitigate the risk of conflict, inform exploration plans and ultimately contribute to the peaceful development of the Moon.

Please note that the present abstract is submitted under the auspices of SGAC's Space Exploration Project Group, as part of the research conducted within the T.U.R.T.L.E. Research Group.

1. Introduction

The world is pervaded by a renewed, unparalleled interest in space exploration. New missions are being planned at an increasing pace by both incumbents and emerging actors from a growing number of countries and with bold visions for our future in the universe. The Moon is in the spotlight as the closest extraterrestrial body where to establish a permanent outpost, as well as for its scientific relevance and for the presence of abundant and strategic resources that can have profound implications on the next steps of human and robotic exploration of the solar system.

In this context, power is a vital element for sustained presence: power will be essential for surviving the long and extremely cold of the unforgiving lunar night, which currently limits most missions' lifespan to 14 days of sunlight. In places like the Poles, operations inside permanently shadowed regions further increase power requirements, while the extension of durably lit areas for sustained power generation shrinks considerably, creating scarcity in the supply of viable photovoltaic energy generation sites.

This great attention to the Moon portends the simultaneous presence of multiple actors operating relatively close to each other in the most interesting regions of our natural satellite. This factor can exacerbate the above-mentioned challenges of the lunar power supply and potentially create tensions among stakeholders.

Power generation, distribution and storage, therefore, are not only mission-critical capabilities for individual users, but they might soon have implications on the equilibria among all the players in the arena.

For these reasons, the present work aims at laying the grounds for a comprehensive assessment of power generation, distribution and storage strategies in critical areas of lunar exploration, in order to identify avenues for the implementation of shared, interoperable and scalable infrastructures tailored to the local environmental features.

The existence of shared power hubs would allow several lunar visitors and settlers to gradually reduce and eventually eliminate individual Electrical Power Systems (EPS), thus decreasing the costs, risks, and complexity of their missions. Organizing power supplies in interoperable nodes would also facilitate maintainability and repairability, and promote faster adoption of new technologies. Moreover, shared power systems could be designed to be modular and easily scaled, thus facilitating adaptation to the evolving user and activities landscape.

The knowledge of the technologies that are best positioned to implement this infrastructure is therefore essential to optimize resources, focus research and development programs, and promote joint efforts.

2. Methods

This work has been carried considering a scenario where multiple actors operate on the lunar surface, with power needs in the order of 10 to 20 kW. Several technologies will be available for such actors, which can be classified according to their role in the power supply chain, namely power generation, distribution, and storage. For each of these categories, the main state-of-the-art technologies were selected for further analysis. The technologies are reported in Table 1 below:

Table 1. Technology selection.

Category	Technologies
Generation	Solar photovoltaic; Concentrated solar photovoltaic, Thermoelectric generators; Nuclear
Distribution	Cabling; Optical Power Beaming; Microwave Power Beaming
Storage	Lithium-ion batteries; Regolith Thermal Mass; Regenerative Fuel Cells; Flywheels; Supercapacitors

As mentioned previously, some of these technologies and their combinations will be more suitable for interoperability and multi-player scenarios than others, depending on a set of evaluation criteria, or figures of merit (FoMs), such as power density, operational temperatures, or environmental stability. Not all the FoMs will contribute equally in establishing what the best option shall be, as some will be more important than others in determining mission success. For instance, in many circumstances, having a high energy density in batteries can be considered more important than having a fast discharge time. In order to find the optimal solution taking all these factors into consideration, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) decision-making tool has been employed. In this analysis, each FoM is assigned with a weight, on a scale from 1 to 5, that represents its relevance on the final evaluation. The list of selected Figures of Merit for the three power Categories is offered below

Table 2. Figures of Merit for Power Generation Technology

Figure of Merit	Description
Power density [W/kg]	Power generated per unit mass

Surface Power density [W/m^2]	Power generated per unit occupied surface area
Lifespan [yrs]	The timespan for which the technology keeps acceptable operational performances
Interoperability	1 = Poor, lack of standards and heritage 2 = Intermediate, some heritage, no standards 3 = Good, consolidated state of practice and standards
Maximum Operating Temperature [K]	Maximum temperature level at which the technology ensures operational performances
Minimum Operating Temperature [K]	Minimum temperature level at which the technology ensures operational performances
Environmental stability	1 = Dust or radiation are a major showstopper 2 = Dust or radiation are a serious threat but effective mitigation strategies exist 3 = Intrinsically resistant/immune to dust or radiation
Risk to operations	1 = Small footprint, low risk of explosions, easy to repair or protect 2 = Medium footprint and explosion risk, tricky to repair or protect 3 = Large footprint and explosion risk, difficult to repair or protect
Scalability	1 = Not designed for modularity, highly cost or mass sensitive to increased demand 2 = Certain degree of expandability through deployment of new units or parts 3 = Modular and tunable, relatively little effort required to scale up

Table 3. Figures of Merit for Power Distribution Technology

Figure of Merit	**Description**
Mass to supply 10 kW across 1 km	Hardware mass required to deliver 10 kW of power to a user located 1 km away
Mass to supply 10 kW across 10 km	Hardware mass required to deliver 10 kW of power to a user located 10 km away
Conditioning at 10 km	Hardware mass required to regulate and condition power at the interface with a user located 10 km away
Lifespan	The timespan for which the technology keeps acceptable operational performances
Operating temperature	Maximum temperature level at which the technology ensures operational performances
Min Operating Temperature [K]	Minimum temperature level at which the technology ensures operational performances
Interoperability	1 = Poor, lack of standards and heritage 2 = Intermediate, some heritage, no standards 3 = Good, consolidated state of practice and standards
Scalability	1 = Not designed for modularity, highly cost or mass sensitive to increased demand 2 = Certain degree of expandability through deployment of new units or parts 3 = Modular and tunable, relatively little effort required to scale up
Environmental stability	1 = Dust or radiation are a major showstopper

	2 = Dust or radiation are a serious threat but effective mitigation strategies exist 3 = Intrinsically resistant/immune to dust or radiation
Risk to operation	1 = Small footprint, low risk of explosions, easy to repair or protect 2 = Medium footprint and explosion risk, tricky to repair or protect 3 = Large footprint and explosion risk, difficult to repair or protect

Table 4. Figures of Merit for Power StorageTechnology

Figure of Merit	Description
Power density [W/kg]	Power amount that can be supplied per unit mass
Energy density [Wh/kg]	Energy amount that can be supplied per unit mass
Volumetric energy density [Wh/m^3]	Energy amount that can be supplied per unit volume
Maximum Operating Temperature [K]	Maximum temperature level at which the technology ensures operational performances
Minimum Operating Temperature [K]	Minimum temperature level at which the technology ensures operational performances
Lifespan [yrs]	Timespan for which the technology keeps acceptable operational performances
Interoperability	1 = Poor, lack of standards and heritage 2 = Intermediate, some heritage, no standards 3 = Good, consolidated state of practice and standards
Environmental stability	1 = Dust or radiation are a major showstopper 2 = Dust or radiation are a serious threat but effective mitigation strategies exist 3 = Intrinsically resistant/immune to dust or radiation
Risk to operation	1 = Small footprint, low risk of explosions, easy to repair or protect 2 = Medium footprint and explosion risk, tricky to repair or protect 3 = Large footprint and explosion risk, difficult to repair or protect
Charge/Discharge rapidity	1 = Hours | 2 =Minutes | 3 = Seconds

Four key locations have been chosen due to their central role in the future of lunar development, as shown in the Table below.

Table 5. Key areas for lunar development and deployment of power infrastructure

Location	Applications	Energy demand sources
Peaks of Eternal Light	Power towers, Sun observatories	Servicing robots, telescopes, ground com, recharge stations
Permanently Shadowed Regions	Infrared telescopy, ultra-cold physics research, mining, cold	ISRU mining equipment, prospectors, rovers, processing plants, observatories and

	sinks	scientific facilities
Far Side Smooth Terrains	Cosmology	Cosmology telescopes, human rovers, antennas
Lunar Pits	Human settlement	Human habitats, crew rovers, airlocks

Weights of each FoM have been differentiated based on the above-mentioned locations, considering that the importance of each evaluation criteria may change based on environmental features. For instance, having low minimum operating temperatures is far more critical in permanently shadowed regions than it is in peaks of eternal light, whereas the opposite is true for maximum operating temperatures.

3. Results and discussion

3.1 Technology survey

The performance scores and the relative weights attributed to each technology, under each figure of merit, based on each of the four selected sites are summarised in the Tables 6, 7 and 8 below.

Table 6a. Performance attributes of generation technologies

	Power dens. [W/kg]	**Surf. Power dens. [W/m^2]**	**Lifesp. [yrs]**	**Interop.**	**Max Op. Temp. [K]**	**Min Op. Temp. [K]**	**Env. Stabil.**	**Risk to ops.**	**Scalab.**	**Source**
Solar Photovolt.	150	300	10	3	393	103,00	1	1	3	[1]
Nuclear	6,7	83000	5	1	1073	1073	3	3	1	[2]
Conc. Solar	500	400	10	3	900	103,00	1	2	3	[1]
Thermoelect.	0,2	133	15	1	600	170	2	2	2	[3]

Table 6b. Weights of generation FoMs for each site.

Figure of Merit	**PEL**	**PSR**	**Far-side terr.**	**Pits**
Power density [W/kg]	5	4	2	3
Surface Power density [W/m^2]	5	5	2	4
Lifespan	4	3	1	2
Interoperability	5	4	2	1
Max. Operating Temp [K]	5	1	3	1
Min. Operating Temp [K]	1	5	3	4
Environmental stability	5	3	2	1
Risk to operation	3	5	1	5
Scalability	5	3	2	1

Table 7a. Performance attributes of distribution technologies.

	Mass for 1 km	Mass for 10 km	Condit. at 10 km	Lifesp. [yrs]	Max Op. Temp. [K]	Min Op. Temp. [K]	Interop.	Env. Stabil.	Risk to ops.	Scalab.	Ref.
Cables	767	8223	454	20	298	273	3	3	1	2	[4]
Laser	1677	1677	638	10	333	283	1	2	2	3	[4]
RF	1229	87872	7505,5	10	473	293	1	2	2	2	[4]

Table 7b. Weights of distribution FoMs for each site.

Figure of Merit	PEL	PSR	Far-side terr.	Pits
Mass to supply 10 kW across 1 km [kg]	2	3	4	5
Mass to supply 10 kW across 10 km [kg]	5	5	3	1
Conditioning mass at 10 km [kg]	5	4	3	1
Lifespan [yrs]	4	4	2	3
Max. Operating temperature [K]	5	1	3	2
Min. Operating Temperature [K]	1	4	3	2
Interoperability	5	5	3	1
Scalability	5	3	2	1
Environmental stability	4	3	2	1
Risk to operation	4	5	1	4

Table 8a. Performance attributes of storage technologies.

	Power dens. [W/kg]	En. dens. [Wh/kg]	Vol. En. Dens. [Wh/l]	Max Op. Temp. [K]	Min Op. Temp. [K]	Lifesp. [yrs]	Interop.	Env. Stabil.	Risk to ops.	Char./ Disch. Rapid.	Ref.
Li-Ion Batt.	1000	150	300	308	243	10		2	1	2	[5]
Fuel Cells	450	400	350	353	333	10	2	2	2	2	[6]
Regolith Therm. Mass	0,32	3,97	11,9	900	500	20	1	3	2	1	[3]
Flywheels	15	10	10	322	288	20	1	2	2	3	[7], [8]
Supercaps	5000	10	8	338	233	15	2	3	1	4	[9], [10]

Table 8b. Weights of storage FoMs for each site.

Figure of Merit	PEL	PSR	Far-side terr.	Pits
Power density [W/kg]	2	4	2	2

Energy density [Wh/kg]	2	5	3	4
Volumetric energy density [Wh/l]	4	5	2	5
Max Operating Temperature [K]	5	1	3	2
Min Operating Temperature [K]	1	5	3	4
Lifespan [yrs]	5	4	4	3
Interoperability	5	5	3	2
Environmental stability	4	3	2	1
Risk to operation	4	5	2	3
Charge/Discharge rapidity	1	5	3	2

3.2 TOPSIS Analysis

Figures below show the results of the TOPSIS analysis. Each bar represents the score obtained by the corresponding technology in a given location. For generation, concentrated solar power is a promising option in that it combines the high heritage - and the consequent interoperability - with photovoltaics with a higher power density and the possibility to be conveniently scaled up. This is especially useful in harnessing the abundant energy available at the peaks of eternal light. Nuclear is the obvious alternative in poorly illuminated regions, driven by the very high volumetric power density. This could in fact reveal particularly useful to deliver sustained and reliable energy supply to power-intensive mining operations inside craters, where extraction and mobility requirements require careful use of the available surface. Here, improving interoperability is a critical aspect that will deserve more attention. Thermoelectric generation still appears to lag behind due to the currently low efficiency and poor heritage.

For storage, fuel cells represent the best solution in each case, thanks to their high energy density and power density and extensive heritage. It is worth noting how batteries, despite being largely used and highly interoperable, become less preferable for high-power applications. Supercapacitors can be a good alternative for particularly intensive tasks where rapid bursts of energy are needed. Storing energy in a regolith thermal mass is currently suboptimal due to the large volumes required, which create obvious operational hurdles. Flywheels are a promising option, but technology is still underdeveloped.

Finally, cables still remain an optimal solution for energy distribution thanks to their inherent simplicity and robustness, high heritage and ease of adaptation. It shall however be noted how laser power beaming might constitute a compelling alternative, thanks to the low hardware mass required over very long distances. The possibility to eliminate potentially hindering cables inside intensely crowded zones also goes to the advantage of this wireless technology.

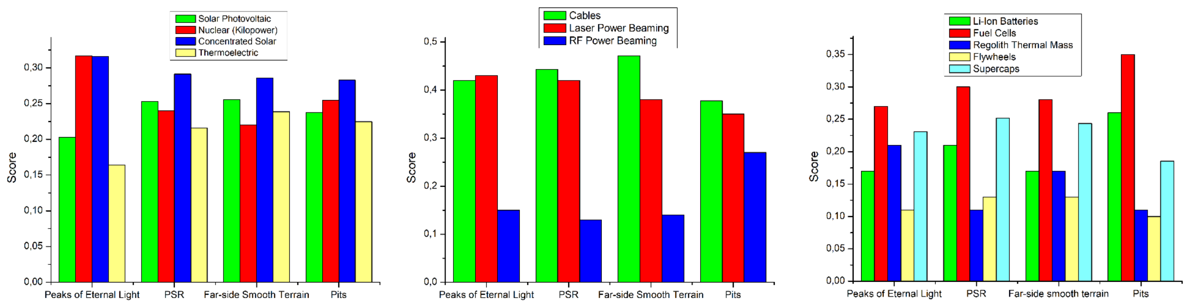

Fig. 1. TOPSIS analysis results.

3.3 Sensitivity Analysis

The goal of this analysis is to show how sensitive scores are to improvements in technological performances. In other words, a fictional 10% improvement is imparted to the technological performances of each technology and fed to the model. The new score obtained by the enhanced technology is compared with the nominal one to assess the overall variations. The magnitude of this variation is an indicator of how important a unit improvement in a particular performance attribute can be in determining the overall fitness of the technology for the final application. The Figures below illustrate the results of this analysis.

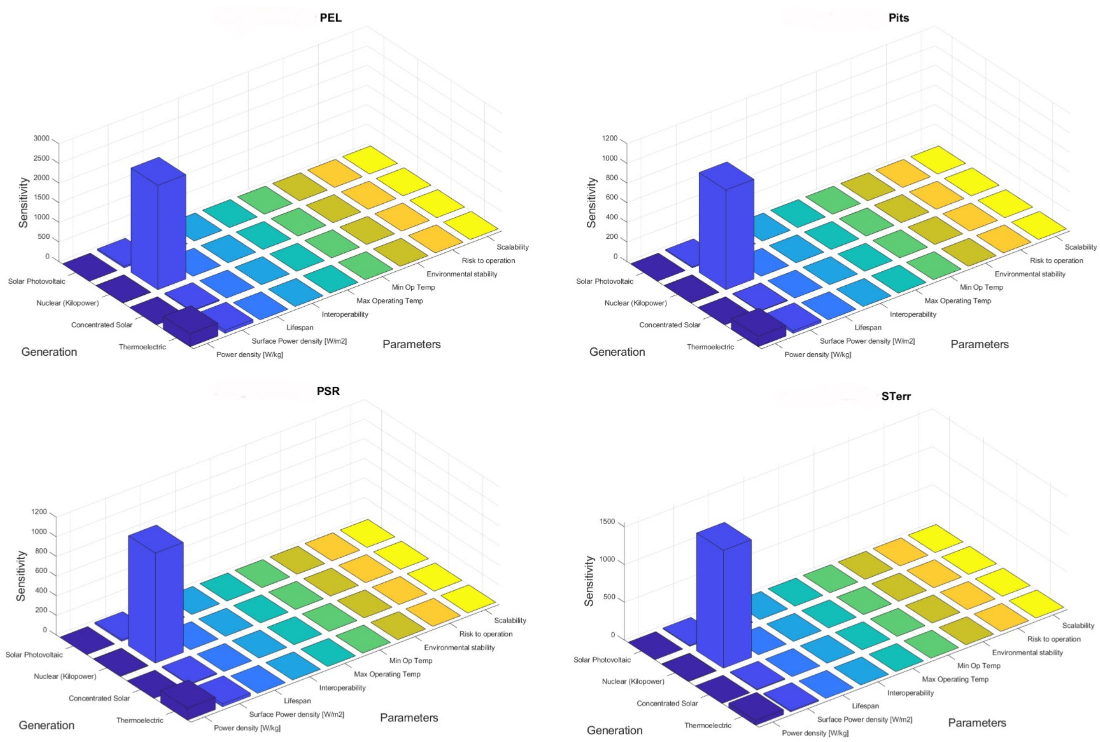

Fig. 2. Sensitivity analysis for generation technologies

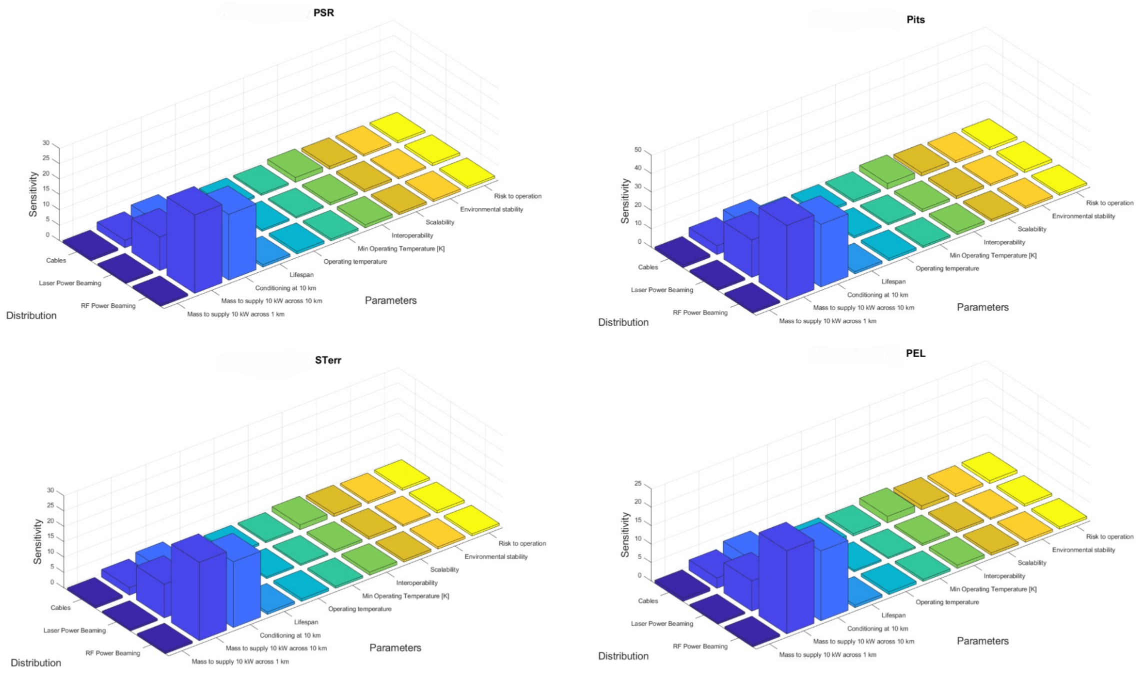

Fig.3. Sensitivity analysis for distribution technologies

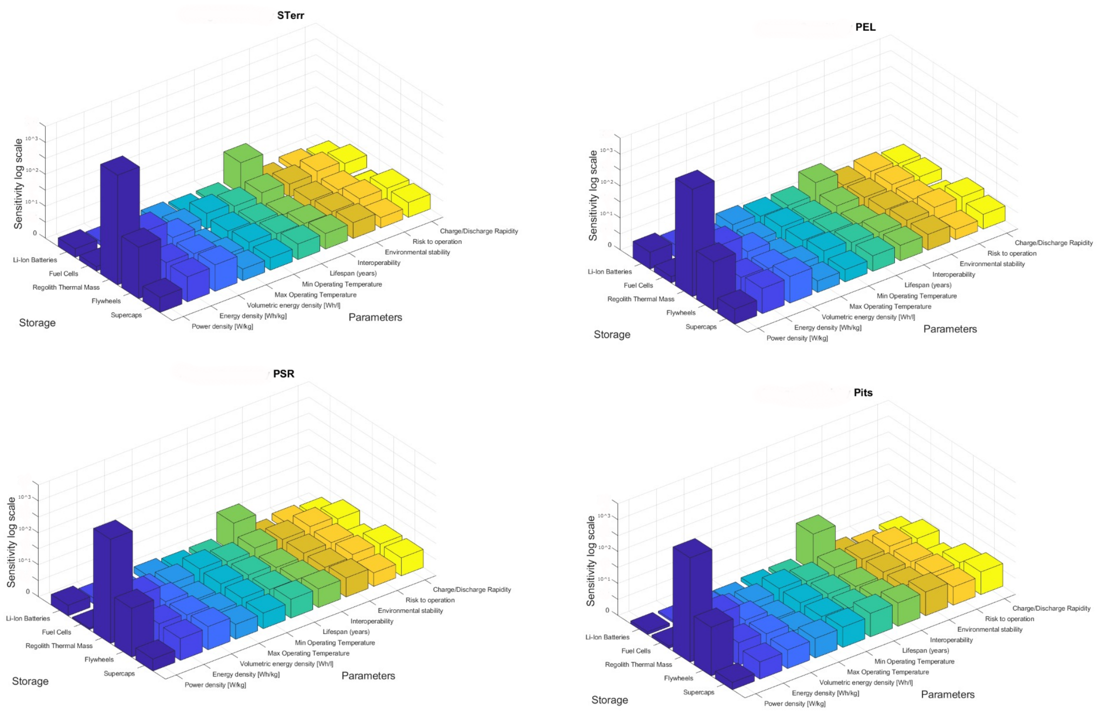

Fig. 4. Sensitivity analysis for storage technologies

3.4 Limitations of this study

The present analysis can hopefully add to the body of studies on power architectures through the multi-stakeholder and the environmental diversification perspective. Some limitations are present at this moment that should be considered by the reader and that should be addressed in future evolutions. The model and the TOPSIS methodology adopted fail to represent accurately qualitative aspects of decision-making. Figures of Merit such as scalability, environmental stability and interoperability have been found hard to quantify. Their importance for this debate should induce new efforts to agree on a shared and quantitative definition. Also, performances of a single technology under certain criteria can differ quite widely depending on designs, materials or suppliers. Typical examples would be different types of cables, nuclear reactors, or solar cells. It would therefore be useful to determine score domains instead of points to paint a more accurate picture. An evolution of this model should also encompass the fact that energy distribution might happen across two or more of the locations selected for this study. Interfaces, regulations and other PMAD aspects could have a non-negligible influence on stakeholders' preferences and should be therefore taken into account. These limitations are reflected into the sensitivity analysis as well, as some representativity is lost in predicting the impact of changes is strictly non-quantitivate variables. Finally, weights of the various Figures of Merit have been attributed by the authors based on current knowledge and on a relativistic basis, in order to capture the differences among the considered scenarios. A wider and more rigorous reiteration of this study should establish weights as averages of different contributions from a representative sample of stakeholders, using a more structured and quantitative approach.

4. Conclusions

In conclusion, this work outlined a preliminary framework in support of decision-makers for the identification of suitable power strategies to be adopted in pursuit of large-scale lunar exploration and utilization programs. Emphasis on interoperability and scalability allowed to identify those technologies with the highest potential to ensure sustained and sustainable cooperation among different actors. Finally, the sensitivity analysis suggested the most effective R&D efforts to be implemented in order to rapidly avance the readiness of these technologies. This work also adds to the overarching effort being undertaken by the Technical Unit Research for a Thriving Lunar Ecosystem (T.U.R.T.L.E.) initiative established withing Space Generation Advisory Council's Space Exploration Project Group. The initiative led to the formulation of a Lunar Exploration Technology Adaptive Roadmap (L.E.T.A.R.) where this study is integrated into a holistic framework encompassing biosphere designs, landing sites analyses, dust-removing vehicles and studies on strategic infrastuctures for multi-actor scenarios. The goal is therefore to set up a space where different stakeholders can tap into and contribute to advance a shared and optimzed vision for technological progress, towards a peaceful and sustainable lunar devlopment.

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