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An Open Dashboard for Lunar Power Candidate Standards

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Lunar Power Standards are critical for cooperative and sustainable development. However, we don't know which standards will work best.

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1. Introduction

1.1 The cost of inaction

On the afternoon of March 11, 2011, Northeast Japan was struck by the fourth strongest earthquake ever recorded.

The tragic event inflicted numerous deaths and vast damage to the national economy and infrastructure. In the wake of the disaster, the country immediately reacted, sending aid and support to the shattered Tohoku region. Energy was among the scarcest and most needed resources, as the Earthquake had caused a massive shutdown of the local power plants. But bringing electrical power to the devastated areas was much harder than expected.

In fact, for electricity to flow from the non-affected West side to the devastated East side, its frequency had to be converted from 60 to 50 Hz, since each side had adopted a different standard for frequency. This required electricity to pass through frequency-converting stations, which had only so much capacity, ultimately constraining the amount of energy that could be transported and prolonging the suffering of the stricken areas.

The story of the 2011 Earthquake is one of many in which a lack of early decision-making can generate disproportionate costs later and one that invites us to reflect deeply on the importance of standards. Still today, poor coordination on power standards keeps dispersing resources, such as in the case of renewable off-grid mini-grids in Sub-Saharan Africa [1]. Here, lack of standardization prevented micro-grids from scaling with the needs of the communities they served and caused numerous difficulties in sourcing quality-certified components and ensuring regular maintenance.

By looking at historical precedents and lessons learned, we have an opportunity to do better in the next instance where our ability to communicate and cooperate effectively will have a massive impact on our chances to succeed: space.

1.2 The value of standards in space

On the International Space Station, the absence of a unique standard - or the presence of two conflicting standards - resulted in the Russian segment having a different ground potential than the other segments, and Russian cosmonauts having to bring specialized inverters to conduct operations, adding extra costs and inefficiencies.

However, the ISS remains a great example of power standardization in space, as testified by the International Space Power System Interoperability Standards (ISPSIS) that have been developed to ensure commonality, safety, and reliability of power onboard the orbiting international outpost. This allowed the consortia of space agencies to cooperate to build something that could not have been afforded individually and to tap into a larger and redundant supplier base that could ensure a constant and reliable stream of parts and components throughout the project's lifetime.

On the Moon, standards will play a similar role, with an extended implication concerning the involvement of private entities and the switch from a paradigm where only institutions are responsible for procuring and operating the assets, to one where privates can play the same roles and offer products and services to institutions or other private entities alike, with the intent of establishing a lunar economy.

For this extended set of stakeholders, establishing shared and standardized lunar power infrastructure has very similar advantages compared to the ISS case: it would allow organizations to reduce and eventually eliminate the reliance on individual, bespoke power systems, slashing costs and increasing the room for additional payloads. It would distribute complex efforts across multiple contributors, leading to a faster growth of capabilities and architectures, ultimately enabling previously impossible accomplishments.

But, somehow differently than in the ISS case, the role of standards can be even more critical on the Moon.

In fact, over the long term, standards can unlock efficiencies and scales that are vital for an economy to take off. And in the short term, they will be key for the initial building blocks to be validated.

In fact, without some early form of standardization, it will be very hard for power users to entirely commit their complex and extremely expensive designs, systems, and missions to a power solution that is either unproven or whose critical elements cannot be sourced by multiple providers. Moreover, testing something on the Moon is much harder than in Low Earth Orbit. Buying into a solution that might not show up is a large risk. If this is true for NASA - which explicitly acts as a market anchor and to reduce risks - it is going to be even more important for profit-driven companies.

As part of its risk-reduction strategy, NASA is indeed supporting the development of a diversified power systems suppliers base, as demonstrated by the multiple contracts awarded for Vertical Solar Array Technology (VSAT) [2] and Fission Surface Power (FSP) [3] plants, as well as for other ways to generate, distribute and store power on the Moon.

However, NASA is not prescribing strict power standards at present, in compliance with its mandate to promote innovation. At the same time, companies are focusing on defining their competitive moats, and, if a standard is defined too early that requires significant deviation from their baseline, it could interfere with their ability to successfully develop and market their solutions.

The conditions for clear standards to emerge and be adopted across the board are therefore not present yet, with power users on one side waiting for demonstrated technologies with fault-tolerant supply chains, and power providers on the other side in the process of evolving these technologies while waiting for a large enough market to solidify and justify standardization.

What we might expect to see is a series of missions that will gradually test multiple solutions and technologies without being entirely reliant on any of those in the first place, to the point when enough heritage will have been accumulated to elect the most promising candidate standards and justify the establishment of more consolidated practices.

In fact, the formulation, adoption, and diffusion of standards cannot be done without the demonstration of their viability, reliability, and safety.

In history, we saw this happening at the end of the "War of Currents" where two contenders, direct and alternating current, were ferociously fighting for the role of standard for power transmission. In the end, AC won, but only after a series of extensive proofs and demonstrations.

Westinghouse had to install AC generators in Great Barrington in 1886, deploy 175 km of transmission line between Luffen and Frankfurt in 1891, and then power the Chicago World's Fair in 1893 before AC could be the choice of current for the Niagara Falls plant that started powering Buffalo in 1896.

Then, it took two or three more decades before the National Electrical Manufacturers Association was established and started to formalize AC standards.

For standards to emerge, it will then be essential to respect this process, which demands consideration of both the strive to innovate and the need for homogeneity and predictability to spur growth.

This situation requires bottom-up strategies and invites to look for low-hanging fruits to gain momentum starting from what is currently being planned and executed rather than proceeding top-down from future concept architectures that are still many years away from being implemented. Now is the perfect time to initiate the conversation.

Is there a way to streamline this process, call for early experimentation, and reduce the risk of multiple standards proliferating in silos, dispersing efforts, and exposing the ecosystem to the costs of inaction?

After extensive review and stakeholder consultation, this whitepaper outlines the possibility of an Open Dashboard for Lunar Power Candidate Standards as a way to keep track of the progress achieved under any standard being proposed for future missions and allow standard implementers to coagulate around what is most needed, most easily proven, and most readily made available by the industry.

The following section will offer an overview of the main sources for lunar power standards as emerged from stakeholder consultation and research. The methodologies described for stakeholder consultation and to elaborate on the input coming from them and additional research are described in Section 3. Section 4 expands on the results of the review, stakeholder consultation, and research process, specifically focusing on the main areas where opportunities for standardization have been identified and with additional recommendations for prioritization. Section 5 expands on the proposal for an Open Dashboard as a framework where the priority areas for standardization can be flexibly developed by the stakeholders. Section 6 lists the key limitations of the study. Finally, Section 7 provides conclusive remarks and additional considerations on the way forward.

2. Sources of lunar power standards from across the world

Power standards on the Moon will draw on existing standards and best practices, merging the experience gained in Low Earth Orbit as well as on past and modern Moon missions. For this research, a multitude of sources of power standards have been reviewed based on historical data and contributions of the interviewed stakeholders. A short overview is presented below, broken down by geographical areas. This choice is dictated by the fact that the adoption pattern of the standards produced by any given standard-making body is reflective of its geographical influence and the States' responsibility for their own space actors. However, there are some instances where standards have been coordinated at the international level. These cases will be addressed right after.

Reviewing and understanding the state of the art allows us to identify gaps, common grounds, and needs for the community at large. Beyond that, it could help anticipate how fragmented the current landscape is, and therefore determine how vast of an endeavour will be necessary to promote cross-coordination or unification of standards. Furthermore, each standard-making body or association offers an example of how standards are set, agreed upon, and enforced, thereby providing valuable inputs on how certain frameworks or sets of practices could translate to the lunar case.

2.1 Europe

When it comes to space standards in general, the main reference in Europe is the ECSS, which is an acronym for European Cooperation for Space Standardization [4]. The ECSS's interests span all the areas of space exploration, including standards on program management, systems engineering, and technical specifications.

The ECSS has not produced standards that are specific to lunar power and seems rather more interested in standardizing lunar and cislunar telecommunications, networking and data, in line with the European Space Agency's (ESA) Moonlight initiative [5]. However, other standards concerning satellite power systems in general (such as those on system testing, reliability, and interfaces) already exist and are well consolidated [6], and it's therefore reasonable to expect that these will serve as a starting point for lunar power standards too.

New standards can be proposed by the members of the ECSS. These include institutional members, i.e. space agencies such as the European Space Agency, the Italian Space Agency, the UK Space Agency, the Centre National d'Etudes Spatiales, and the Deutsches Zentrum fur- Luft und Raumfahrt, as well as industry members, which are collectively represented by the industry association Eurospace [7].
Standards then undergo a review process during which they are scrutinized by a technical committee and refined in an iterative process until they are approved. The registry of standards is then updated, offering traceability of the old standards that have been replaced [8].

The adoption of the ECSS standards is ensured mainly by the European Space Agency, which prescribes their adoption to its contractors. The ECSS is a great example of standard formulation and implementation internationally, although coming from a geographical area with a high pre-existing political and institutional integration among states.

With the focus on space resources demonstrated by ESA and local actors with the creation of the European Space Resources Innovation Research Center (ESRIC) and the In-situ Space Resources (ISRU) start-up ecosystem in Luxembourg [9], a substantial interest in lunar power standards has been found among many of the interviewed organizations, given the importance of said standards to scale and secure sustainable resources utilization.

Finally, many European institutions and companies can count on the heritage of the ISS and are actively involved in the development of the Lunar Gateway and the overall architectures for the Artemis program, where adaptations to power standards for the Moon will be discussed.

2.2 United States

In the United States, NASA has conducted extensive standardization work for air and space systems across the years, merging and endorsing [10] standards coming from a multitude of different sources into a unified, cohesive NASA Technical Standards Program (NTSP) [11] supported by the Chief Engineer and the Headquarters. The sources [12] include many military standards from aeronautics, as well as standards proposed by other Voluntary Consensus Standard Development Organizations such as the American Institute of Aeronautics and Astronautics (AIAA), while new standards were created where gaps existed.

Organizations like the AIAA have members from industry, academia, and institutions, who can all volunteer to take part in committees dedicated to the development of new standards. The process [13] involves the submission of a new proposal to the leadership of AIAA and a series of steps where the proposal undergoes public ballot and review, and the right of appeal is granted to the members before official approval. Voluntary Consensus Standards are overall very important across the US [14], as a means to ensure successful integration between Agencies and industry.

As far as military standards are concerned, these have been highly relevant for lunar surface power. For example, the MIL-STD-3899 is advertised by Commercial Lunar Payload Services (CLPS) company Astrobotic in their payload user guide as the standard connector for power [15].

Military standards for aircraft electric power systems (MIL-STD-704A) have been used for the Apollo Lunar Module [16] as well, and the MIL-STD-461 [17] is a common reference for electromagnetic compatibility. The very common 28V power bus architecture seen across many lunar assets and satellites has roots in bus voltage standards for military aircraft. A standard describing such architecture has been released by AIAA [18].

NASA itself has also been an active proponent of standardized systems for lunar power, as in the case of the Universal Modular Interface Converter (UMIC) [19], a universal AC/DC converter conceived to facilitate the connection of diverse loads to surface-based microgrids running on diverse power sources, like Vertical Solar Arrays Technology (VSAT) and Fission Surface Power (FSP) plants. The two later initiatives are also a testament to the great interest of NASA in developing a robust power infrastructure on the Moon, which will at some point call for a parallel standardization effort. It is however worth noting that, at the time being, the two Request for Proposal issued by NASA before the award of contracts for the development of VSAT and FSP did not contain an express requirement on the adoption of any particular standard. On the other side, the microgrid described in NASA's work [20] suggests that optimal parameters for power distribution across the grid would be 3-phase, 3000 VAC, at a frequency of 1000 Hz.

The USA also boasts a fervid ecosystem of private organizations supporting either independent or Artemis-related lunar exploration programs. The companies involved in the abovementioned CLPS program are a good example. Many of these companies publicly advertised 28V power buses for their systems, while other details of power interfaces and specifications are left to be defined on a case-by-case basis. It’s also worth mentioning the organizations participating in the Lunar Terrain Vehicle development [21]. In its Request for Proposal, NASA asked the contractor to “design, build, test, and certify a power exchange connector” [22] and also mentioned the International Space Power Interoperability Standards (ISPSIS) among the reference documents.

An interesting case of a bottom-up standard development initiative is the “Lunar Operating Guidelines for Infrastructure Consortium” [23] also known as LOGIC. LOGIC is led by Johns Hopkins University’s Applied Physics Lab and DARPA. LOGIC derives from DARPA’s Luna-10 Capability Study and gathers companies, universities, and government organizations in workshops to discuss gaps and opportunities in standards for lunar surface infrastructure, including power, and formulate consensus-driven recommendations. LOGIC participants also compiled a very useful list of existing standards that are or can be considered a reference for lunar missions.

LOGIC has not completed its course yet, but many interesting conversations have been sparked among the participants, who have discussed topics such as how a grid should prioritize the dispatch of electric power to users in case a new user arrives or in case of contingency. While this is certainly a very fascinating question, it is less clear whether a scenario for which such a standard can be relevant would unfold in the short term. In fact, many of the stakeholders interviewed for this research have not indicated this as their most pressing need for standardization.

Another challenge for LOGIC could be to find endorsement from institutional Standards Developing Organizations (SDOs) that can consolidate these standards and ensure their legitimacy and adoption by the community, for instance by having NASA mandate their implementation in fulfilment of the obligation with its contractors. This shall go in parallel with mechanisms to manage standard review and update processes, which seem currently absent. Despite these limitations, LOGIC sets a very interesting precedent for standard formulation in this new and exciting field.

Overall, a rich industrial ecosystem that is proactive towards standard development, the existence of SDOs exercising voluntary-consensus standard development like AIAA, and the presence of NASA with a track record of lunar operations and standard development, position the USA as a leader in lunar power standards.

2.3 Japan

The Japanese Aerospace Exploration Agency (JAXA) produced several standards [24] for space exploration systems, including standard JERG-2-214 [25] for power subsystem design. The associated documentation and the technical literature on Japanese spacecraft emphasized the importance of learning and experimentation in the development of standards and their key role in guaranteeing mission success by ensuring that the lessons learned are implemented.

Efforts toward the standardization of electric power system standards have been made also concerning the Small Scientific Satellite Series [26], as a way to streamline the creation of a small-scale, low-cost, short-lead-time satellite supply.

Most recently, the SLIM lunar lander offered a great opportunity to learn more about the functioning of power systems on the lunar surface, thereby representing a great source of empirical evidence to inform the definition and refinement of lunar power standards.

Although specific information on the process of standard development could not be found, Japan can leverage a wealth of existing standards and experience in lunar exploration that make it a strong hub for the creation of new standards for lunar power, and it is reasonable to expect that many of these will be used for the development of the Japanese pressurized rover [27] for the Artemis program.

2.4 China

China has conducted a vast lunar exploration program, with the latest Chang'e 6 missions successfully returning to Earth with samples collected on the far side of the Moon. Chang'e is part of a broader exploration effort, culminating in the International Lunar Research Station initiative, where China plans to establish a permanent research station on the surface of the Moon in cooperation with Russia and other international partners.

The Chinese National Space Administration leverages a comprehensive body of standards for its space program [28]. Interest in lunar power standards can be driven by the plan to collaborate with other international partners on the ILRS project, which comprises in fact an "Energy Module" on the lunar surface to supply power to the activities of the research station and resource utilization.

The Chang'e program itself can serve as a good framework to test and develop lunar power standards, given the integration process of payloads - many of which are international - with the Chang'e landers. These standards can therefore serve as a ground for further development of future lunar power standards for the research station and its users. The station, with the multitude of assets, facilities, and power plants shown in conceptual designs [29], will necessitate power standards to ensure reliable operations and interoperability.

2.5 India

India accomplished historic lunar missions with its Chandrayaan program, gaining highly valuable heritage on space systems, including power, and their performances on the Moon. India adheres to international standards on space systems such as those proposed by the International Standards Organization, but also endogenously develops its own body of technical standards for space through the Indian Space Research Organization (ISRO), which authors the ISRO Technical Standards (ITecS) [30,31], as well as through the Bureau of Indian Standards [32].

2.5 Russia

Russia counts on a rich and well-known history of lunar exploration and space systems development. This progress has been captured by numerous standards, most notably the GOST standards. While GOST standards cover a wide variety of fields and industries, many are specific for space and the Moon, such as Standard R 25645-161:1994, "The Surfaces Of Moon, Mars and Venus - The Radio-Physical Parameters" [33]. Russia is also, together with other nations, formally involved in the ILRS, which could be then expected to be a prolific ground for the definition of lunar power interoperability standards [34].

2.6 International Standard Development Initiatives

As seen in the sections above, power standards in space and for the Moon tend to develop regionally. However, several efforts took place at the international scale that have great potential to translate to forthcoming cooperative lunar exploration endeavours.

2.6.1 Deep Space Interoperability Standards

This collection of standards spans across a multitude of areas, such as telecommunication, data, and also power. For power, in particular, the reference is the International Space Power System Interoperability Standards (ISPSIS), which have been developed by the ground national space agencies that built and managed the International Space Station. The ISPSIS prescribe rules on power systems safety, operations and testing while being design-agnostic.

Given the long heritage of these standards and their international nature, they are being adapted now for the Lunar Gateway [35], which induces us to speculate that they can constitute a very good source and reference for lunar surface power standards too, although they have been conceived for a finite-sized orbital outpost, and not necessarily for a flexible infrastructure that includes surface assets.

The other limitation of ISPSIS is also that they are the result of inter-agency discussion. While agencies keep the industry in this loop, there is no clear evidence in the ISPSIS development practices of a formalized and systematic way to incorporate industry contribution and its rights to appeal, review, or submit new standards.

2.6.2 International Standard Organization

The International Standard Organization (ISO for short) is the world's largest standard development organization. In 1947, ISO established Technical Committee 20 (TC20) on Aircraft and Space Vehicles [36]. In 1983, Subcommittee 1 on Aerospace Electrical Requirements was established within TC 20, followed in 1992 by Subcommittee 14 on Space Systems and Operations.

To date, Subcommittee 14 includes the following 16 participating members: Australia, Brazil, China, Finland, France, Germany, Greece, India, Italy, Japan, Romania, Russian Federation, Spain, Ukraine, the United Kingdom, and the United States.

The Subcommittee produced 193 standards so far [37], including ISO 10788:2014 on lunar simulants, ISO 14302:2022 on electromagnetic compatibility requirements, and ISO 11892:2012 on interface control documents. The Subcommittee also has 43 standards under development, including ISO/AWI TR 25087 on electric wire derating, and ISO/CD 20256.2 on solar cells calibration.

This suggests that spaces exist where some form of interaction and grounds for future work on lunar power standards are being established internationally, among actors that would otherwise be considered in competition.

This is crucial, especially for long-term perspectives and human spaceflight. In fact, while standards might initially support integration and interoperability of robotic systems and missions within regional ecosystems and exploration programs, there could be situations in the future where cooperation at larger scales is necessary. For instance, should American and Chinese astronauts be on the lunar surface at the same time, they would be obliged under Art. V of the Outer Space Treaty to ensure each other assistance in case of emergency or distress. In practice, offering assistance would be much easier, and risks of casualties or injuries could be considerably lower, if some shared standards existed, including on power systems.

ISO is however an association of typically national SDOs, with wide multi-stakeholder, consensus-seeking processes. While this is certainly good, it might suffer from lengthy timelines. For instance, the project for the formulation of the abovementioned ISO Standard 10788:2014 on lunar simulants was approved in 2010, but the standard was only published in 2014. Other standards could be approved more rapidly where more prior art and informal alignment already exists, but it might not be the case for lunar power considering the young age of the field.

3. Stakeholder consultation and gap assessment: sample description and analytical methods

A thorough review of the state-of-the-art technology, scientific literature, and standard-making bodies and initiatives led by industry, government, or institutions across the globe, presented above, was conducted to lay the grounds for this research.

Subsequently, one-to-one interviews have been conducted with sixteen (16) organizations actively involved in lunar exploration and development - i.e. currently planning to perform a lunar mission and/or to take part in long-term lunar settlement - to probe their stance concerning power standards. While a standard template for interviews was not used, stakeholder consultations generally aimed at qualitatively assessing their posture on the following main factors:

- Degree of adoption of power standards from one or multiple sources, and motivations driving this adoption.
- The importance attributed to power standards for the achievement of their goals in the near and long term.
- Awareness of existing needs, gaps, and opportunities in standardization
- Current involvement in standard-making initiatives or interest in taking part in these.

The composition of the interviewed stakeholders is shown in the charts below.

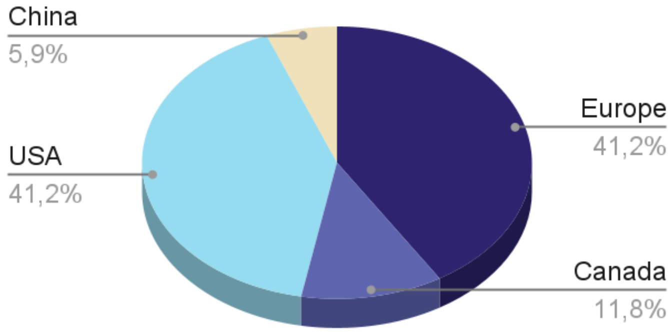

Figure 1: Country of origin of the interviewed stakeholders

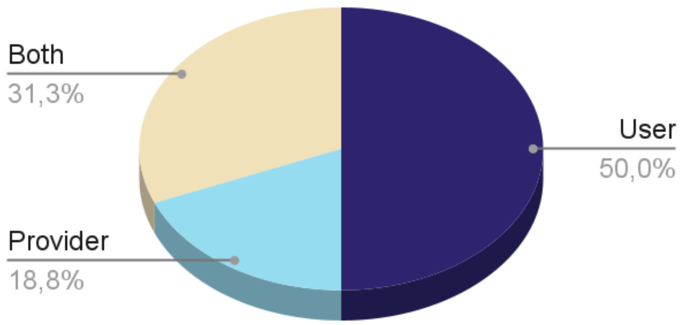

Figure 2: Breakdown among power consumers, producers, and both providers and users.

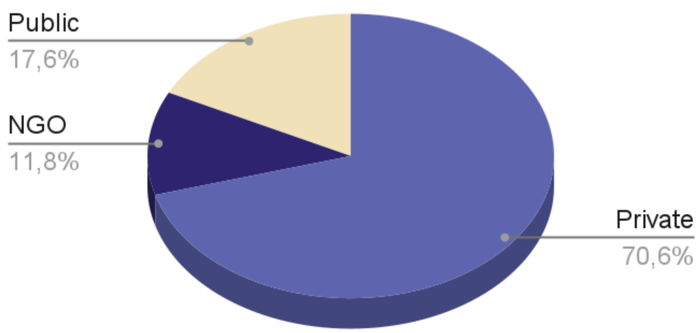

Figure 3: Main categories of interviewed organizations.

After researching the state of the art and completing stakeholder consultation, a set of eight critical technical areas were identified by the author where opportunities for standardization could exist. These areas were found to be either among the most recurrently mentioned by stakeholders or the most frequently addressed by working groups and other research studies and will be presented in the following section.

To make these findings more actionable, a preliminary priority among these technical areas has been subsequently established using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) multi-criteria decision-making method [38]. This approach allows to establish a ranking among several solutions (i.e. the 8 priority areas) based on how they perform under multiple criteria. The best option is then selected as the furthest from an "ideal worst" and the closest to an "ideal best". More details on the approach can be found in [38].

For this study, four criteria were chosen by the author based on research findings, and their justification will be provided in the "Results" section. Similarly, performance ratings under each criterion were established with a semi-quantitative approach, i.e. by attributing a rating from 1 to 5 to each area, 1 being the lowest performance score and 5 being the highest. Ratings were then normalized. The ratings were not given directly by the stakeholders and shall not be considered an official and commonly agreed expression of their stance, so they should only be considered as a provisional attempt by the author to coarsely parse through the technical areas and facilitate a discussion on prioritization.

The TOPSIS method also allows one to attribute a weight to each of the criteria so that one criterion might weigh more (or less) than the others in determining the final rating of a given technical area. However, for this study, all the criteria have been given the same weight to avoid introducing further bias from the author on the final results. The author's input is still present in the ratings attributed to each of the technical areas under the four criteria. However, this input was informed by the extensive research and consultation work done before.

After a review of the state of the art, stakeholder consultation, assessment of the gaps, and prioritization of the opportunities, a proposal was advanced to concretely pursue these opportunities, which will be presented in Section 5.

4. Results and discussion

The analysis of the state-of-the-art and the interviews conducted across the international community have revealed a complex landscape where many forces and actors are shaping different approaches to lunar power standards unfolding at various scales (national and international), involving different types of actors (industry, space agencies, government institutions) and following different frameworks and principles (concertation among institutional SDOs, community-led workshops, voluntary-consensus, dialogue between industry and government or institutions). Of the organizations interviewed for this study, several are directly involved in standard-development organizations or initiatives, whereas others are not. The breakdown is shown in the chart below.

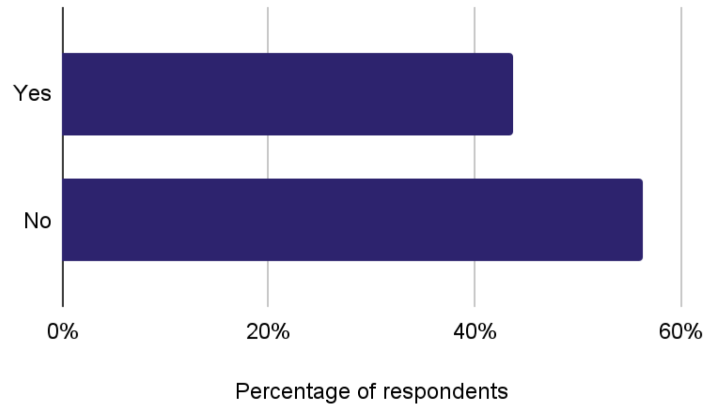

Figure 4: Breakdown of participants according to participation in standard-development organizations or initiatives

As mentioned in the previous section, consultation of all these organizations and other domain experts, together with the analysis of the state of the art and the technical literature, led to the identification of eight technical areas where candidate standards are required to address the currently perceived gaps. The areas are presented in the following subsections.

4.1 Interface converters

Similar to NASA's UMIC, interface converters are meant to electrically connect loads to sources, ensuring that the current and voltages are appropriately handled and converted to match the requirements of both sides. Standard interface converters are particularly useful when a multitude of power sources and power loads with common requirements are expected. The desirable levels of voltages and currents change according to the application. For instance, small mobility platforms can be ok with a 28 VDC, low current input, but large ISRU plants might require far larger currents for their energy-intensive processes.

4.2 Grid transmission voltage and frequency

These parameters are critical to each electric grid on Earth, and so will be on the Moon. They will determine how safely and efficiently energy can be transported as a function of the distances it needs to travel. If a grid is developed on the Moon, voltages, and frequencies will likely be among the first aspects to be standardized.

4.3 Grid balancing

Balancing a grid means ensuring that an equilibrium is maintained between power supply and demand. This is necessary to ensure nominal grid operations. A standard for grid balancing becomes relevant when the number of power sources and power users connected to the grid, as well as the amount of power that each can generate or consume, change regularly and unpredictably over time.

4.4 Dust-tolerant connectors

On the Moon, dust is a ubiquitous challenge. Abrasive, electrostatically charged, micron-scale dust grains can easily infiltrate cavities and cover surfaces, including those of a lunar electric plug, which could be disrupted, potentially causing harm to the assets connected. A standard could cover how such risk shall be countered, and according to which procedures this shall be verified.

4.5 EMI and EMC on the Moon

Electromagnetic compatibility (EMC) must be insured in power systems according to the electromagnetic environment they operate in, to prevent unwanted events such as Electromagnetic interference (EMI) or failure of electrical and electronic parts. The Moon has a peculiar radiation and electromagnetic environment that shall be considered in outlining a standard covering this topic for forthcoming power plants or grids. Thanks to past missions and existing standards, a good amount of knowledge is available

4.6 Power system robustness to solar storms

The absence of a strong magnetic field on the Moon makes its infrastructure particularly vulnerable to solar storms and the effects of rays and particles from outer space. Any power infrastructure shall be robust against these factors. A standard here would regulate how power systems would withstand such events or recover from them, especially when their functioning is critical to human activities.

4.7 Low-temperature batteries rating

Batteries suffer from cold environments. Their actual capacity at low temperatures is lower than the nominal capacity that is advertised, as the ability to charge and discharge is also compromised by low temperatures. Batteries are ubiquitous and play a key role in each lunar mission. Yet, no standards exist to rate them for low-temperature environments.

4.8 Charging interfaces

Several of the organizations interviewed have expressed their need to clarify how their asset could connect with a charging solution. Determining input voltages and currents, as well as mechanical and electrical interfaces, and being aware of how ripples, transients, overcurrents, and other perturbances are controlled are the main needs that a standard would have to cover. Charging is very relevant in terms of timeframes and relevance to current missions since many of the upcoming use cases are going to be more similar to small-scale mobile assets requiring charge rather than fixed installations requiring baseload power from a microgrid.

4.9 Criteria for prioritization

A second key finding of this research concerns the reasons preventing lunar power standards from being intentionally developed and pursued at the present time. As anticipated in the Introduction, the main reason why standards are not explicitly requested by a market that is very aware of their importance is that this market needs those standards and their underlying technologies to be further demonstrated first. On the other side, a part of the industry is used to tailoring solutions and is developing technologies that are key to obtaining their competitive advantage, while waiting for a cleared market demand to solidify and justify the implementation of any standard.

This means that the technical areas to focus on to gain initial momentum with standard development shall be those that can affect the widest potential market while being able to rely on already existing standards or technical knowledge. For these reasons, the eight technical areas were rated under the following four criteria:

1. Their *time relevance*, whereby a standard is given a higher score the sooner its implementation is going to be required on the Moon
2. Their *community relevance*, whereby a standard is given a higher score if it can be expected to repeatedly and predictably affect a higher number of missions, and a lower score if it's specific to a very peculiar mission
3. The *degree of lunar heritage,* whereby a standard is given the highest score if past missions have already demonstrated its core tenets on the lunar surface, and the lowest score is given if the idea is completely unproven, even on the ground
4. The *reliance on existing standards,* whereby a higher score is attributed when previous standards exist that are a good analogy or starting point for the proposed standard.

Table 1 below shows the ratings and the final normalized ranking order. As mentioned above, the scores have not been given directly by the interviewed organizations and do not reflect their official position.

Standard Type	**Time relevance**	**Mission relevance**	**Lunar knowledge**	**Existing standards**	**Rank**
Low-temperature batteries rating	5	5	2	2	100%
Charging interfaces	4	5	1	3	99%
EMI and EMC on the Moon	3	2	2	4	88%
Interface converters	3	3	2	3	84%
Dust-tolerant connectors	3	4	2	1	63%
Robustness to solar storms	3	2	2	2	61%
Transmission voltage and frequency	2	2	1	1	21%
Grid balancing	1	2	1	1	0%

Table 1: Priorities among technical areas for future candidate standards

It is worth stressing that these scores are notional and only meant to capture first-order differences among the different technical areas.

This preliminary ranking would suggest that low-temperature battery rating and charging interfaces could benefit the most from standardization given the large and short-term impact that they would have. In parallel, the relative lack of lunar knowledge suggests that more investigation is required. In other words, an opportunity is found here to fill a critical gap. Other technical areas such as the one about EMI and EMC on the Moon rank high mainly thanks to the existence of similar standards, which suggests that these could be a low-hanging fruit to set precedents and working principles without threatening innovation.

It shall be noted that this list of standards is non-exhaustive. Other technical areas could be considered depending on the time frame and stakeholders. For instance, standards to rate solar arrays against dust accumulation, or standards to ensure interoperability and interchangeability of portable power elements of EVA suits from different national programs. These did not seem to emerge predominantly during the research.

Even if a priority was established among technical areas, such as the one proposed above, there would still be an outstanding issue: how do we know how well the candidate standards within each area are progressing and performing in practice, and when they can be ready for adoption?

5. An Open Dashboard

What emerged quite unequivocally from this study is a relative lack of empirical evidence on many physical and engineering topics that are relevant for standard formulation and implementation. Without such standards, users will struggle to commit to providers' solutions, becoming unable to decrease their mission development and execution costs.

Without a sufficient amount of users, providers will not have incentives to create and adhere to standards.

While this is not critical at the moment, since most missions are part of finite government-funded programs specifically intended to test and experiment with new technology, what's ultimately at stake is our collective ability to sustain a continued and scalable effort to develop the Moon.

This work therefore proposes the creation of a simple, open system to track the progress made on proposed *candidate standards* and to allow entities interested in that evidence-based standard to manifest their intent to implement it.

The main features or functions of this system can therefore be summarized as follows:

1. A candidate standard can be proposed by a potential implementer, which would offer a description of such a standard and receive critique or inquiry.
2. For any given candidate standard, a record of progress and achievements towards its demonstration would be kept and made available to the public. For instance, for a dust-tolerant connector, a timeline would be made available showing that the connector has just passed an active, dirty TVAC test and that a demonstration mission is currently planned for two years.
3. For any given candidate standard, other providers could manifest their interest in offering it as well. For instance, if the Lunar Power Supply Company A proposed a standard for power distribution, the Lunar Power Supply Company B could declare its intent to follow that standard as well.
4. In parallel, users would also be able to manifest their interest in adopting any given candidate standard.

Such a system would have the following benefits:

1. By soliciting the entry of a *candidate standard*, it would prompt systematic reflection and contribution to the area of standards, capturing a wide picture of the most readily available solutions while giving providers frameworks and

inspiration to eventually turn their innovative technologies - or portions of them - into future candidate standards.

2. By tying to each standard its maturation history, inclusive of empirical evidence about its effectiveness and susceptible to updates whenever new evidence becomes available, it would provide solid traceability on progress and transparency on reliability and performances, giving users the opportunity to make the most informed decision, and enabling space agencies and the market to identify gaps to be filled.
3. By letting providers decide which candidate standards to follow, it would avoid top-down decisions risking to stifle innovation, accelerating the convergence to a set of standards that innovators are comfortable implementing, as these would not be seen as threatening their competitiveness. In other words, the low-hanging fruits could be identified more easily, setting precedents to further build upon.
4. By disclosing the number of providers willing to implement a given candidate standard, users would have strategic intelligence on their supply chains, and could more easily decide to commit since their mission would not rely on a single provider, triggering a virtuous cycle of adoption and consolidation.
5. By ranking standards according to their maturity, proximity to existing standards, market demand, and industry willingness to comply, a clear priority would be established to harmonize and focus future research, and an opportunity would be given to the market anchor tenants (such as NASA or ESA) to readily identify the most promising candidate standards to acknowledge and legitimate and to inform their maturation.
6. By letting users indicate which standards they are more interested in, providers would know where a critical user mass is accumulating and would have a more tangible incentive to provide that standard or to offer a better alternative. The absence of such demand has been indicated by some of the interviewed organizations as a leading reason for the lack of interest in standards.
7. At the international level, standards for global interoperability would gradually emerge as a result of an ongoing and iterative comparison.

The figures below show two hypothetical user interfaces for such a dashboard.

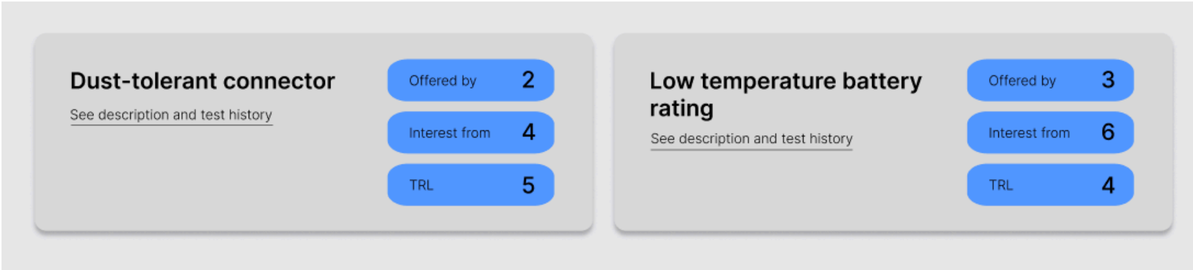

Figure 5: The Dashboard showing two candidate standards under two of the eight technical areas identified in the study, and their key metrics.

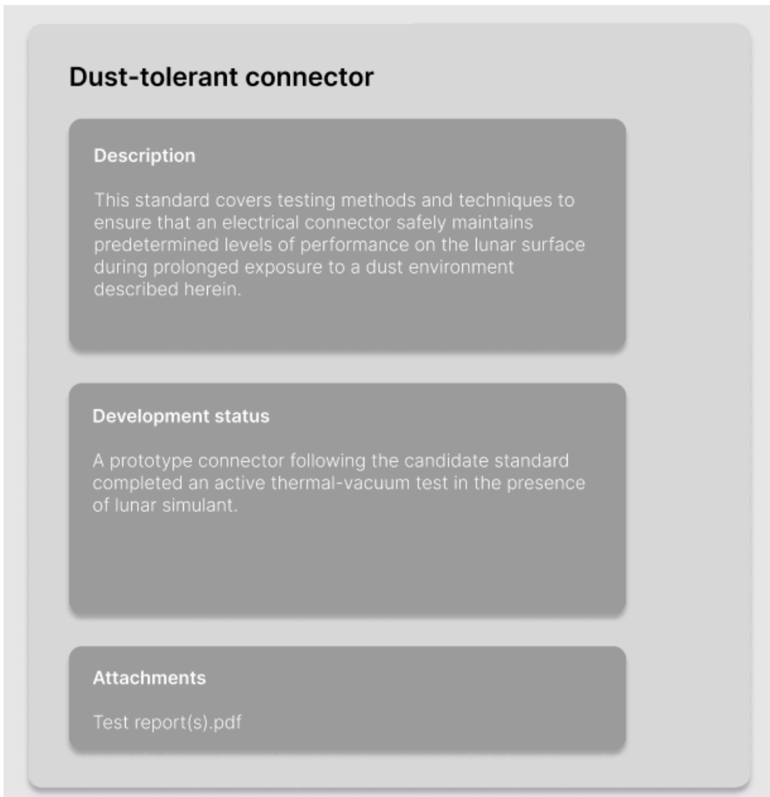

Figure 6: Organized information about a potential candidate standard.

Overall, a simple, open Dashboard would let the community interact autonomously and iteratively align their interests, starting from viable use cases. It shall also be noted that, while this study proposed some priority among key technical areas for standard development, such a Dashboard shall ultimately be as inclusive as possible and allow for the introduction and monitoring of other standards too.

5.1 Challenges

5.1.1 Intellectual Property

An issue that we might expect to emerge as standards are consolidated and accepted by the community is that of patents and intellectual property. In the world of standards, the so-called “standard essential patents” (SEPs) exist, which are patents covering technology that is necessary to implement a given standard.

On the Moon, we might expect that some of the technology required to implement standards will be patented by some organizations. When that is the case, that organization holds powerful leverage and can use it to introduce barriers against competitors or to increase its profits to the detriment of other standard implementers.

An interesting terrestrial analogy is represented by the smart metering systems being developed to promote the energy transition towards green energy sources and power systems. For these smart meters to be implemented, several SEPs are necessary. However, the SEPs holders apparently refused multiple times to license the patents at low costs to the smart meter developers, according to a position paper published in 2021 by the European Association of Smart Energy Solution Providers [39].
One solution to this issue, that might serve as a useful analogy for the lunar case, is licences granted under the FRAND - Fair, Reasonable and Non-Discriminatory - principles. These principles are meant to ensure that SEPs are licensed at the right conditions for the implementers to pursue their legitimate goals sustainably while recognizing the value of the innovation captured by the SEP. On Earth, FRAND licenses are facilitated by organizations that manage pools of SEPs for various technologies and can act as independent intermediaries between licensors and licensees. In some instances, supervising and enforcing the application of FRAND principles required the intervention of regulatory bodies.

On the Moon, the Dashboard could serve as an open workshop to stimulate the development of new standards while giving visibility to new and promising innovations, streamlining the replacement of obsolete standards, and removing barriers to new entrants.

5.1.2 Governance and Legitimacy

Another key challenge is the definition of a clear governance structure for the Dashboard. Since this is conceived to be an open, community-driven framework where information can be shared on a voluntary basis, it could be expected that preferred standards would ultimately gradually emerge as the result of regular user contribution and interaction, provided perhaps that some user verification mechanisms are put in place.

A second challenge is legitimacy: even if the community elected some standards, those would not necessarily be adopted if the market did not require them. Part of the solution to this issue is involving all sides, as described above, gradually expanding the community such that its role can be considered in higher regard. Another possibility could be involving other SDOs as partners. Both these issues have many implications and will require more work.

6. Limitations of this study

This study has several limitations that shall be considered and potentially addressed in future work. Firstly, the sample of interviewed organizations does not include participants from Japan, India, Russia, and other present or future space-faring nations. Therefore, the conclusions from this study shall not be considered reflective of the global international landscape.

Secondly, the technical areas selected for further study are not a comprehensive list. Other areas might have been missed that can be reasonably considered equally important if not more, such as human-rated systems, wireless power beaming, or nuclear sources.

Thirdly, as already mentioned, the ranking obtained through the TOPSIS method is a function of the scores attributed by the author based on the research and learnings, and not a direct expression of the stakeholders' views. The same holds for the selected criteria. While the intent was to simply show a potential approach toward addressing this issue, community input would surely increase the value of the results.

Finally, the Dashboard proposal is preliminary, and further work is required to more thoroughly elucidate all the implications.

7. Conclusions

Global interest in the Moon has never been greater. Never have we witnessed such an internationally diverse effort, the strongest in its intention to establish a sustained and sustainable presence.

This is the best opportunity that we have to devise all the technologies, business cases, policies and governance frameworks to kickstart a peaceful and thriving development of the Moon, as our ability to accomplish this is vitally dependent on the simultaneous concentration of viable, collective, and sustainable initiatives.

Standards will be an essential ingredient for this endeavour. By making power systems scalable, shared, and interoperable through standards, we will have established a critical piece of lunar infrastructure that will dramatically lower the cost of access and development by eliminating the burden for each mission to build and operate its dedicated power source, and by unlocking the possibility to do more for longer.

This study offered a review of the state of the art of power standards for space and the Moon in particular, corroborated by extensive consultation with a wide set of stakeholders. Lunar power standards can be defined starting from a multitude of sources, drawing from existing frameworks and bodies of knowledge consolidated within and across several countries in the world with space and Moon exploration experience. Stakeholder interviews corroborated and expanded these findings, and allowed us to get a sense of the short-term needs and of the factors that can practically obstacle or accelerate standard adoption.

While the importance of lunar power standards is almost unanimously acknowledged within the community, their definition - and subsequent adoption - is currently slowed down by a relative lack of empirical data on the technical performances of the technologies that could be at the base of such standards, as well as by a lack of clear and wide market demand. These roadblocks can be addressed by prioritizing focus areas and streamlining the development of key technologies through shared, iterative, and community-driven standard selection and development frameworks. This possibility can be pursued through an open dashboard where candidate standards, their maturity, and their multilateral appetite for them can be shared and kept updated. Future work might include further iteration on this concept to clarify and advance more aspects related to its implementation.

By promoting traceability and transparency on our progress on candidate standards, we can considerably anticipate the moment when our efforts will be truly collective, potentially before the point when self-sufficient Moon exploration programs will have become unbearably expensive.

If the cost of inaction can be our multi-planetary future, we must act now.

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Appendix A - List of stakeholders

The following people and/or organizations have been consulted and interviewed to learn more about the current state of Lunar Power Standards and have given their consent to be mentioned in this Appendix. Other stakeholders have not provided written consent yet. This list might be updated in the future. As mentioned above, it's here important to highlight that the conclusions and proposals offered with this work are not coming directly from these stakeholders and do not reflect their official position on the topic.

- Adriatic Aerospace Association (Croatia)
- David Tunney, Canadensys (Canada)
- Eamon Carrig, ICON (USA)
- Steve Dust, International Lunar Astronomical Observatory (USA)
- Gary Lai, Interlune (USA)
- Sotirios Zormpas, Lunar Outpost EU (Luxembourg)
- Alessandro Lovagnini, Maana Electric (Luxembourg)
- Jeffrey Csank, NASA (USA)
- Dallas Bienhoff, OffWorld (USA)
- Matyàs Hazadi, Puli Space (Hungary)
- Davide Carabellese, Thales Alenia Space Italy (Italy)
- Jarred Olson, The Aerospace Corporation (USA)
- Justin Zipkin, Volta Space Technologies (Canada)
- Francesco Liucci, European Space Agency (Netherlands)
- Victoria Schein, European Space Agency (Netherlands)