Overview of NASA's Watts on the Moon Challenge Phase 1

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As NASA works to extend human exploration of the solar system, unprecedented capacity for electrical and thermal energy will be needed to support sustained human presence and the beginning of industrial activity on the Moon. Solar energy is abundant on the lunar surface but extended night hours (up to 350 consecutive hours) and extreme temperature change from daylight to nighttime operation creates complexity for solar power use. Analogous issues arise on Earth, where demand for additional renewable energy generation, including solar, is rising, but better power management, distribution, and energy storage solutions are needed to address intermittency and resiliency, among other issues. To accelerate the development of technologies for power distribution and energy storage that can operate in extreme lunar conditions, NASA's Centennial Challenges Program launched the Watts on the Moon Challenge in September 2020. Submissions for Phase 1 of the challenge were due in March 2021 and winners were announced in May 2021. This paper provides an overview of the challenge, key technical requirements, outcomes from Phase 1, and an update on Phase 2 of the challenge, which is currently ongoing.

I. Introduction

On December 11, 2017, the White House issued the Presidential Memorandum on Reinvigorating America's Human Space Exploration Program, which amended a Presidential Policy Directive on National Space from June 2010 [1]. The Memorandum calls for the U.S. to:

"Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations."

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This Memorandum set in motion reinvigorated efforts by NASA to use the Moon as a proving ground for testing technologies and creating the mature systems needed for future long-term planetary missions to Mars and beyond. These efforts are primarily organized through NASA's Lunar Surface Innovation Initiative (LSII) program. LSII, working with other key NASA partners, is charged with developing a technology portfolio to enable human and robotic exploration on the Moon and future operations on Mars.

LSII is focused on six areas to spur the creation of new technologies and accelerate the technology readiness of systems and components needed to meet the 2017 policy directive:

1. In Situ Resource Utilization
    a. Collect, process, store and use material found or manufactured on the Moon
2. Sustainable Power
    a. Enable continuous power throughout lunar day and night
    b. Scale to tens of kilowatts for long-term surface operations
3. Extreme Access
    a. Demonstrate technologies enabling humans or robotic systems to efficiently access, navigate, and explore previously inaccessible lunar or planetary surface or subsurface areas
4. Surface Excavation and Construction
    a. Demonstrate technologies enabling affordable, autonomous manufacturing or construction (e.g., of a landing pad, berm, or shielding) using lunar surface materials
5. Lunar Dust Mitigation
    a. Develop concepts to mitigate lunar dust hazards, enabling affordable, sustained operations both on the lunar surface and with transfers to and from Gateway or other orbital platforms
6. Extreme Environment Functionality
    a. Develop technologies and other strategies to enable rovers, manipulators, and other systems to operate throughout the full range of lunar surface conditions including lunar noon (up to 423 K), night (down to 93 K), multiple day/night cycles, and permanently shadowed regions (down to 33 K)

In 2019, NASA began exploring how the Centennial Challenges Program (CCP) could complement other ongoing efforts under the LSII program, including around sustainable power. CCP was established in 2003 to conduct prize competitions to support NASA's exploration goals [2]. It was inspired by other successful prizes and challenges, including the 1919 Orteig prize for the first nonstop aircraft flight between New York and Paris won by Charles Lindberg [3] and the $10 million Ansari XPRIZE, which sought to lower the risk and cost of going to space by incentivizing the creation of a reliable, reusable, privately financed, crewed spaceship [4]. CCP seeks innovative solutions to technical problems that can drive progress in aerospace technology and be of value to NASA's missions in space operations, science, exploration, and aeronautics. The program encourages the participation of independent teams, individual inventors, student groups, private companies of all sizes, and competitors from diverse backgrounds. Since its inception, CCP has successfully launched and operated 22 challenges.

II. Watts On the Moon Challenge

In 2019 and early 2020, CCP in conjunction with subject matter experts from the NASA Glenn Research Center and Frangione + Associates Innovation Advisors, a contractor with expertise in designing and operating open innovation challenges, explored focus areas and potential technical requirements for a challenge to address power delivery and energy storage in the extreme environmental conditions of the lunar surface. In July 2020, a draft version of the challenge was offered for public comment under a NASA Request for Information (RFI) [5]. NASA received 17 comments to the RFI and integrated them as appropriate.

Phase 1 of the Watts on the Moon Challenge was approved by NASA in August 2020 and launched on September 25, 2020.

A. Challenge Overview

The Watts on the Moon Challenge was designed to incentivize flexible, robust solutions that address NASA technology gaps in power transmission and energy storage and that can progress toward flight readiness and future operation on the lunar surface.

As NASA works to extend human exploration of the solar system, unprecedented capacity for electrical and thermal energy will be needed to support sustained human presence and the beginning of industrial activity. For many years, NASA has had robust research and development efforts related to power generation, but solutions that would enable use of solar energy on the lunar surface remain nascent. Solar energy is abundant on the lunar surface but extended night hours (up to 350 consecutive hours) and extreme temperature changes from daylight to nighttime operation creates complexity for solar power use. New and innovative concepts for power distribution, energy management, and energy storage could help address future energy needs on the lunar surface and beyond. Such concepts may also have important synergies with terrestrial energy needs related to deploying intermittent renewable energy generation and increasing efficiency and resiliency of the grid.

The Watts on the Moon Challenge was designed to address these gaps. The challenge offers up to $5 million in prizes as well as potential opportunities for innovators to test their solutions at NASA facilities. The challenge was designed to have two phases.

B. Phase 1 Objectives

Phase 1 of the Watts on the Moon Challenge sought to identify new concepts for power distribution, energy management, and energy storage solutions that could operate in the extreme cold, darkness, and vacuum conditions on the lunar surface.

To encourage a wide array of ideas and maximize the number and diversity of potential competitors, the challenge was framed around three hypothetical "mission activities" similar to the types of activities NASA plans to conduct on the lunar surface. Each mission activity was designed to be judged as a separate challenge, and teams were encouraged to submit concept designs for multiple mission activities.

Phase 1 offered prizes totaling up to $500,000. NASA planned to award up to three grand prizes in the amount of $100,000 (one for each mission activity) and up to four additional prizes of $50,000 to the next highest scoring teams in one or more mission activities.

C. Mission Activities and Technical Requirements

The challenge guidelines presented three hypothetical mission activities. These mission activities were the "problems" that teams were asked to address in their concept design solutions. For each mission activity, teams were asked to address technical requirements, including a hypothetical concept of operations and operational power requirements, as well as other issues (e.g., development plans, budgets, risk assessments, and intersection with terrestrial energy needs) that would help the judges assess each team's potential for developing the technologies in the next phase of the challenge.

The challenge guidelines explained that all mission activities occur in the vacuum of the lunar environment and specifically at a lunar polar region where the availability of sunlight is irregular. Two mission activities take place inside a lunar crater that is a permanently shadowed region (PSR), in a polar region where the sky is a thermal radiation sink at 4 kelvins (K) (equivalent to -269 °C) to which surfaces radiate heat. Everything inside the lunar crater is surrounded by the same 4K radiative sink, and items touching the lunar surface must also contend with heat conduction into low thermal diffusivity material at low temperatures on the order of 100 K (-173 °C). In this PSR, sunlight rarely or ever intrudes; as a result, the environment is permanently cold and acts as a "cold trap" of volatile chemical species, especially ice.[*]

The challenge guidelines noted that all mission activities assume four hypothetical NASA assets: a power generation plant, mobility platform, water production plant, and oxygen plant as shown in Fig.1. The NASA power generation plant provided is deployed on the rim of the crater. Teams were not responsible for conceptualizing a power generation source and, in fact, were discouraged from including power generation in their concept designs. The hypothetical NASA power plant was described as having the following characteristics:

- Located outside the crater in a fixed location near the crater rim
- Unobstructed line of sight to any assets operating inside and outside the crater
- Provides 10 kilowatts (kW) electrical power at 120VDC (volts of direct current)
- Complies with the SAE AS5698 power quality specification
- Provides power only during illuminated periods, which are at least 300 hours in duration
- The lunar resource collection and processing assets in the crater operate one kilometer (1 km) or more distant from the power plant while performing their primary tasks

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[*] "Ice" refers specifically to "water-ice" as opposed to other types of ice found in space locations, such as "carbon dioxide ice" found on Mars.

The challenge guidelines also noted that teams should not include in their concept designs the design or implementation of any features of the hypothetical NASA assets and may not assume any modification of these assets to change the operational power requirements. Teams were allowed to use the NASA mobility platform in their concept design solution in any of the mission activities (with the operational power requirements noted in Tables 1, 2, and 3).

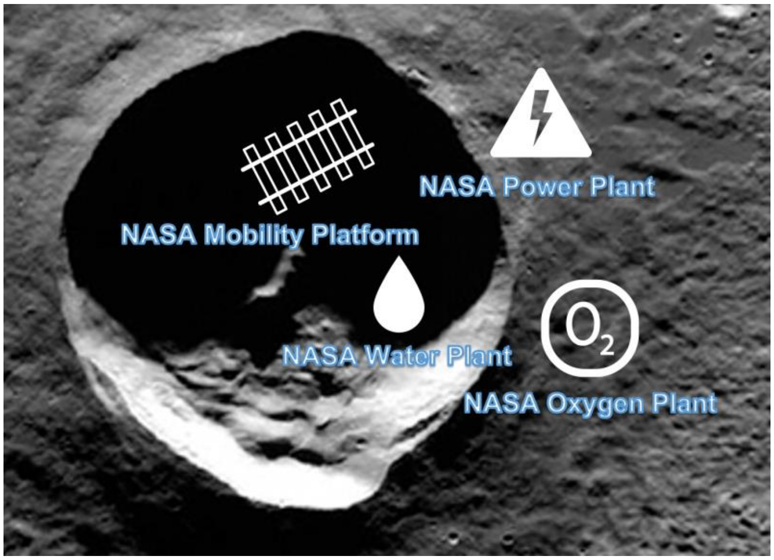

Fig. 1 Hypothetical NASA assets in Watts on the Moon Challenge Phase 1.

Finally, although the mission activities did not specify a requirement for system mass, the challenge guidelines encouraged teams to consider how they would minimize the system mass of their proposed solution, because system mass will be an important consideration for transporting any solution to the lunar surface in the future.

Table. 2 Detailed technical requirements for Mission Activity #1 – Collecting Regolith

Summary	**Concept of Operations**	**Operational Power Requirements**
A mobility platform collects and delivers water-bearing material to a water extraction plant inside the crater. Teams must propose a solution to deliver power from the power plant to the mobility platform.	The mobility platform is required to collect and deliver water-bearing material for 100 hours and operates one (1) km from the power plant on the crater rim. During the required total of 100 hours of collection, the vehicle may conduct specific electric motor driven tasks, such as excavation, loading, traversing to and from the water plant, and unloading—resulting in variations of power needs over time. The mobility platform is capable of descending into and climbing out of the crater if needed, but this capability is not required to perform the material collection and delivery task.	Initial descent of the mobility platform into the crater is required, consisting of a 10-hour trip with a continuous 150 W_E load for vehicle mobility. The platform will have an additional 5 W_E load for every additional 1 kg of payload added by the solution. During the descent the vehicle requires an additional continuous 50 W_{TH} delivered at 50 °C for thermal protection. If needed for their solution, Teams may assume a thermal interface between an external heat source and the mobility platform that is 10 cm by 10 cm, providing 0.5 W/cm^2 flux. Inside the crater, electric power is required in repeated one-hour cycles of ½ hour at 100 W_E followed by ½ hour at 200 W_E. 50 W_{TH} is required continuously to maintain an operable environment for the mobility platform components.

	Due to issues related to long-term exposure to the severe cold environment in the crater, Teams must provide continuous thermal protection heating. The total Mission Activity time may not exceed 200 hours.	If climbing out of the crater is needed as part of the power delivery solution, the platform can reach the power plant in a 10-hour ascent, requiring continuous 150 W_E for vehicle mobility. The platform will have an additional 5 W_E load for every additional 1 kg of payload added by the solution. During the ascent the vehicle requires an additional continuous 50 W_{TH} delivered at 50 °C for thermal protection. If needed for their solution, Teams may assume a thermal interface between an external heat source and the mobility platform that is 10 cm by 10 cm, providing 0.5 W/cm^2 flux. Return descent requires the same time and power. During any time outside the crater, the platform will require continuous 50 W_E to operate, but no thermal protection power.

Table. 2 Detailed technical requirements for Mission Activity #2 – Water Production Plant

Summary	**Concept of Operations**	**Operational Power Requirements**
A water extraction plant operating inside the crater extracts and purifies water from delivered material. Teams must propose a solution to deliver power from the power plant to the water extraction plant.	The water production plant operates continuously to produce clean water from ice-bearing regolith delivered by the mobility platform. The stationary plant is located one (1) km from the power plant on the crater rim. The icy regolith is 2% ice mass fraction and 98% dry regolith (the average specific heat of regolith is 1.2 kJ/kg-ºC). The icy regolith is heated from -220 ºC to 200 ºC to fully extract the water. The plant produces 10 kg of water during a 100-hour operating cycle, at the end of which the water is dispensed from the plant for delivery. Supporting a water delivery is not a required part of this activity. Dry regolith at 150 ºC is continuously discarded. Due to issues related to long-term exposure to the severe cold environment in the crater, Teams must provide continuous thermal protection heating.	Inside the crater, electric power is required in repeated one-hour cycles of ½ hour at 500 W_E followed by ½ hour at 1,000 W_E. A continuous thermal protection load of 200 W_{TH} delivered at 50 °C is required to maintain an operable environment for the plant components. If needed for their solution, Teams may assume an interface between the heat source and the water production plant that is 20 cm by 20 cm, providing 0.5 W/cm^2 flux. If the mobility platform is used in the proposed solution, an initial descent of the mobility platform into the crater is required, consisting of a 10-hour trip with a continuous 150 W_E load for vehicle mobility. The platform will have an additional 5 W_E load for every additional 1 kg of payload added by the solution. During the descent, the vehicle requires an additional continuous 50 W_{TH} delivered at 50 °C for thermal protection. If needed for their solution, Teams may assume a thermal interface between an external heat source and the mobility platform that is 10 cm by 10 cm, providing 0.5 W/cm^2 flux. If the mobility platform is used in the proposed solution, the platform can reach the power plant in a 10-hour ascent, requiring continuous

	Total mission activity duration is three water deliveries and up to 300 hours.	150 W_E for vehicle mobility. The platform will have an additional 5 W_E load for every additional 1 kg of payload added by the solution. During the ascent, the vehicle requires an additional continuous 50 W_{TH} delivered at 50 °C for thermal protection. If needed for their solution, Teams may assume a thermal interface between an external heat source and the mobility platform that is 10 cm by 10 cm, providing 0.5 W/cm^2 flux. Return descent requires the same time and power. During any time outside the crater, the platform will require continuous 50 W_E to operate, but no thermal protection power.

Table. 3 Detailed technical requirements for Mission Activity #3 – Oxygen Production

Summary	**Concept of Operations**	**Operational Power Requirements**
An oxygen-producing pilot plant outside the crater extracts oxygen from the delivered material. Team must propose a solution to address electrical and thermal energy needs of the oxygen production.	Outside the crater, the oxygen-producing pilot plant experiences irregular periods of solar illumination and eclipse over the course of a 709-hour lunar diurnal cycle. The plant location was selected to ensure that the initial illuminated period in each diurnal cycle is 300 hours long. The remaining time is approximately split between 50% illuminated and 50% eclipsed on an irregular schedule, with no eclipsed period longer than 30 hours and all illuminated periods at least 20 hours long. The power plant only operates during illuminated periods. However, to avoid damage from thermal cycling of high temperature components, the oxygen-producing pilot plant must produce oxygen continuously over the full 709-hour diurnal cycle. The oxygen-producing pilot plant, located 100 m from the power plant, extracts oxygen continuously at a rate of 1 kg/hour from dry regolith that is 14% oxygen by mass (average specific heat of regolith is 1.2 kJ/kg-ºC). Oxygen extraction requires heating regolith from 200 ºC to 1,800 ºC.	During both illuminated and eclipsed periods, the oxygen-producing pilot plant requires 5 kW_E continuously. Because of the large thermal mass produced by the plant, there is no additional thermal protection requirement. If the mobility platform is used in the proposed solution, initial traversing from the power plant to the oxygen-producing pilot plant requires one hour, 50 W_E to operate plus an additional 5 W_E for each additional 1 kg of payload added by the Team. If the mobility platform is used in the proposed solution, the platform can traverse the distance between the oxygen plant and the power plant in one hour, requiring 50 W_E to operate plus an additional 5 W_E for each additional 1 kg of payload added by the Team.

	The plant continuously discards regolith mass at 1,100 ºC at a rate proportional to the oxygen production rate.	

Table 4 summarizes the three hypothetical mission activities. See Tables 1, 2, and 3 for additional technical specifications for each mission activity.

Table. 4 Summary of Mission Activities in Watts on the Moon Challenge Phase 1

Mission Activity	Description
Mission Activity #1 – Collecting Regolith	A mobility platform collects and delivers water-bearing material to a water extraction plant inside the crater. Teams must propose a solution to deliver power from the power plant to the mobility platform.
Mission Activity #2 – Water Production Plant	A water extraction plant operating inside the crater extracts and purifies water from delivered material. Teams must propose a solution to deliver power from the power plant to the water extraction plant.
Mission Activity #3 – Oxygen Production	An oxygen-producing pilot plant outside the crater extracts oxygen from the delivered material. Teams must propose a solution to address the electrical energy needs of the oxygen production.

D. Assessment and Judging

A total of 110 points were available, weighted as follows: up to 30 points for scientific and technical merit; up to 30 points for how well teams addressed the requirements of the mission activities; up to 30 points for feasibility of the proposed system; up to 10 points for system fabrication and test plans; and up to 10 bonus points for relevance to terrestrial applications. Teams were required to achieve a minimum score of at least 50 points to be eligible for a prize.

E. Phase 1 Submissions

In Phase 1, the Watts on the Moon Challenge received 60 total submissions and 43 eligible submissions from 28 distinct teams. Nine teams submitted entries for multiple mission activities, as allowed by the challenge guidelines and encouraged by NASA. Four teams submitted for two mission activities (two teams for Mission Activity #1 and #2; and two teams for Mission Activity #2 and #3) and five teams submitted for all three mission activities. One team submitted a total of four concepts, including two concepts for Mission Activity #2.

Each mission activity received a significant number of eligible submissions, exceeding NASA’s expectations. Mission Activity #1 received the most submissions (19 submissions). Mission Activity #2 and #3 received the same number of submissions (12 submissions each). NASA considered Mission Activity #3 to be the most complex of the mission activities and was particularly pleased that so many teams chose to submit concepts for it.

Phase 1 attracted 28 distinct teams. The vast majority of teams (~86% or 24 teams) were made up of industry players. The remaining teams came from academia (~11% or 3 teams) and citizen inventors (~4% or 1 team).

The challenge was open to U.S. teams only. Teams came from a diversity of states across the U.S (see Fig. 2). Four states had multiple teams participating: California (5 teams), Texas (4 teams), Colorado (3 teams), and Virginia (2 teams).

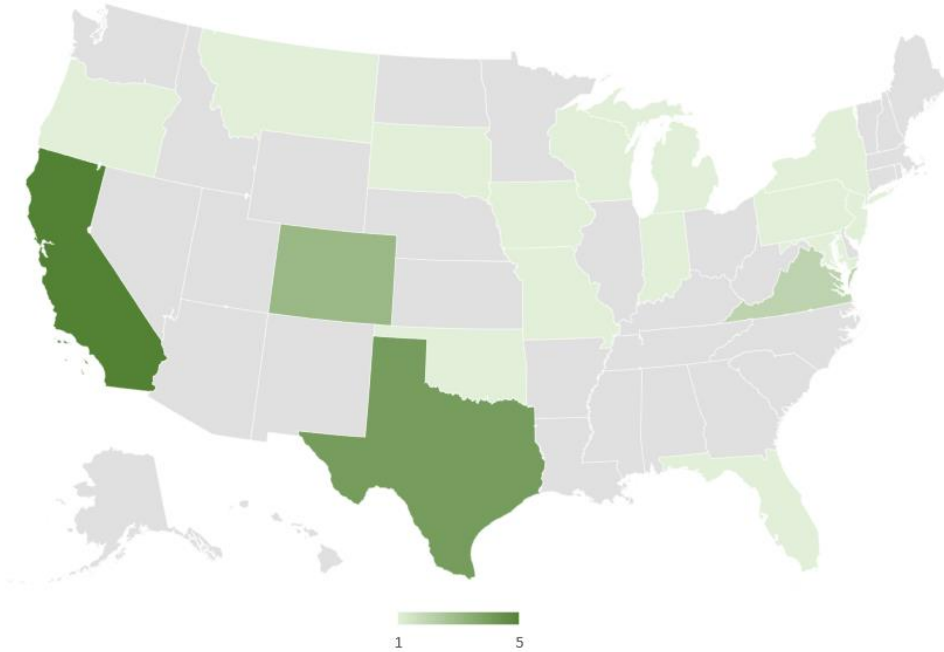

Fig. 2 Geographic distribution of teams in Watts on the Moon Challenge Phase 1.

Teams submitted a diversity of solutions for each mission activity. Many solutions included a combination of power transmission and energy storage technologies, and a few teams proposed leveraging unique characteristics of the lunar surface, including lunar regolith. Table 5 shows the breakdown of common energy technologies across eligible submissions. Submissions also included a number of other technologies, including: supercapacitors; compressed air energy storage; superconducting magnetic energy storage; thermal energy storage systems; microgrids; wireless induction charging systems, artificial intelligence; mechanical launching systems for deploying technologies on the lunar surface; gravitic engines; and a battery-swapping robot.

Table. 5 Breakdown of energy technologies proposed in Watts on the Moon Challenge Phase 1

Type of Energy Technology	# of Eligible Submissions Proposing Each Technology
Wired power transmission	**14**
Wireless power transmission/ power beaming	**15**
Battery energy storage	**22**
Fuel cell energy storage	**4**
Flywheel energy storage	**2**

F. Phase 1 Winners

On May 20, 2021, NASA announced $500,000 in awards for seven winning teams across the three mission activities [6]. The winners included a mix of known players in space technologies and newcomers that had not previously worked with NASA on energy technologies.

Three of the winners offered solutions focused on power beaming, and four of the winners included battery systems in their solutions. Two winners included wired power transmission in their solutions. Mission Activities #1 and #2 each had three winners—one grand prize winner ($100,000) and two prize winners ($50,000 each); Mission Activity #3 had one grand prize winner. Table 6 summarizes the winners, concepts, and awards.

Table. 6 Summary of Watts on the Moon Challenge Phase 1 Winners

Mission Activity	Team	Location	Concept	Award
Mission Activity #1	Astrobotic Technology, Inc.	Pittsburgh, PA	A system of tethered rovers that deploy power cable plus battery energy storage	$100,000
	Team KC Space Pirates	Kansas City, MO	Power beaming with battery energy storage	$50,000
	Team Moonlight/ University of California, Santa Barbara	Santa Barbara, CA	Power beaming	$50,000
Mission Activity #2	Planetary Surface Technology Development Lab/ Michigan Technological University	Houghton, MI	A system of tethered rovers that deploy superconducting power cable	$100,000
	Team Lunar FuelPod	Johnstown, CO	Intelligent microgrid with a system of battery-powered “pods”	$50,000
	Team Astrolight	Rochester, NY	Power beaming	$50,000
Mission Activity #3	Skycorp, Inc.	Santa Clara, CA	An "intelligent Space Systems Interface (iSSI)" that provides power and data connections combined with battery energy storage	$100,000
TOTAL AWARDED				**$500,000**

G. Status of Phase 2

On February 23, 2022, NASA launched Phase 2 of the Watts on the Moon Challenge. In this phase, NASA is seeking power transmission and energy storage solutions that can be designed and built and then tested in simulated lunar conditions, and that are well-positioned to progress toward flight readiness and future operation on the lunar surface after the challenge. Phase 2 will have three rounds of competition (called competition “levels”) and up to $4.5 million in prizes.

Instead of the multiple mission activities utilized as a framework in Phase 1, NASA narrowed the technical requirements in Phase 2 to a single power delivery scenario that all teams are required to address. The challenge guidelines lay out a detailed power load profile requiring teams to 1) draw power from an intermittent power source and deliver power continuously to a load bank; 2) operate in simulated lunar temperatures and vacuum; 3) operate continuously without any additional power generation; 4) demonstrate a capability to deliver power over a distance of three kilometers (3 km); and 5) optimize system mass and system efficiency.

In Phase 2, NASA is requiring a level of detail in submissions similar to what would be required in an engineering preliminary design review in Competition Level 1 and an engineering critical design review in Competition Level 2. NASA will also conduct a site visit to see and review each team’s technology and progress at the end of Competition Level 2. Up to four teams will have an opportunity to test their technologies at a NASA facility in Competition Level 3; the team that successfully delivers power according to the power load profile and best optimizes system mass and system efficiency will be the winner.

Registration for Phase 2 closed on June 15, 2022. Phase 2 was open to U.S. teams only. Teams were not required to have participated in Phase 1 in order to compete in Phase 2. NASA received 25 eligible submissions for Phase 2.

On August 16, 2022, NASA announced seven winners for Phase 2, Competition Level 1 [7]; each received a $200,000 prize and moves onto Competition Level 2. Three of these winners were also Phase 1 winners. Table 7 lists the Phase 2 Level 1 winners.

Table. 7 Watts on the Moon Challenge Phase 2, Competition Level 1 Winners

Team	Location
Electric Moon	Columbus, OH
Orbital Mining Corporation	Golden, CO
Philip Lubin's Team*	Santa Barbara, CA
Michigan Technological University Planetary Surface Technology Lab*	Houghton, MI
Skycorp*	Santa Clara, CA
Virtus Solis Technologies Inc.	Troy, MI
X-Wheel Inc.	Hialeah, FL

At the end of Competition Level 2, up to four teams (out of these seven) will win $400,000 and move onto Competition Level 3. At the end of Competition Level 3, $1 million is available for first place and $500,000 is available for second place. Phase 2 is expected to be completed by September 2024.

III. Conclusion

NASA's goal of sustainable presence on the Moon needs development of critical technologies that are reliable and can operate for long periods of time in extreme environmental conditions. Watts on the Moon Challenge provides an opportunity for academia, industry, and general public to develop and test power management, distribution, and energy storage solutions that enable long term human presence on the Moon and beyond. Phase 1 of this challenge resulted in a wide variety of ideas from conventional and non-conventional sources. Through Phase 2 of this challenge, we hope to identify unique high TRL technologies that will be launched and demonstrated on the Moon in the near future.

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* Phase 1 winner