A PROPOSED METHODOLOGY FOR QUANTITATIVE LUNAR RESOURCE ASSESSMENTS (QLRA).
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Introduction: There are a variety of natural lunar resources that will be invaluable for a sustained human presence on the Moon [1-3]. The methods used by the United States Geological Survey (USGS) to assess natural resources on Earth provide a well-tested framework for similar assessments of lunar resources [2,3]. Here we propose a general methodology that could be applied to quantitatively assess energy, mineral, and water resources on the Moon. This methodology is most directly derived from that used for USGS Quantitative Mineral Resource Assessments [4] but brings in some concepts from petroleum resource assessments [5] and adjusts some terms to be more consistent with terminology from lunar and planetary science and exploration. It is also generally compatible with the LORS 101 standard being developed internationally [6].

Classification: "*Resource*" is an imprecise term in planetary science but can have very strict definitions in economic geology. The proposed resource classification system attempts to strike a pragmatic balance by focusing on whether (a) deposits of the resource have been mapped, (b) the technology exists to convert the resource into a commodity, and (c) the commodity can be obtained economically. Adapting existing terminology, we propose that resources without mapped deposits be labeled "*undiscovered*" and those with mapped deposits as "*identified*." We also recommend adopting the standard used in USGS energy resource assessments, and consider technology that is likely to be available in the next 30 years to assess if a resource is "*technically recoverable*." This could be equated to NASA Technical Readiness Level 3 or higher.

Reserves. On Earth, the term "*reserves*" is restricted to technically recoverable resources for which the overall benefits of converting the resource into a commodity is demonstrated to outweigh its costs. Over millennia, humans have developed monetary and economic systems that distill a whole host of complex factors into dollars to help determine whether or not to pursue extraction of a resource. This system is imperfect and continues to evolve, but is undeniably effective.

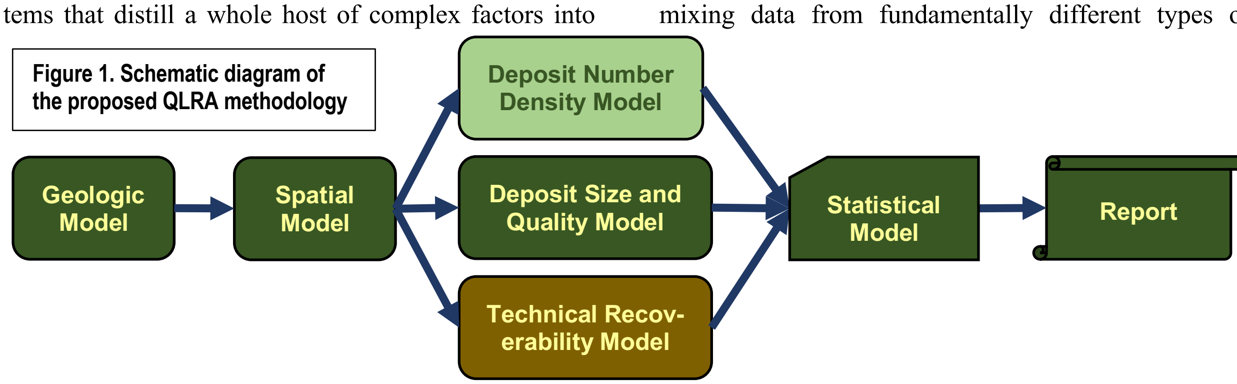
However, it may be decades before the cislunar commercial ecosystem is sufficiently mature for market value to define which technically recoverable resources are reserves. We propose the solution is to embrace the existing concept of budgets within a space exploration context (e.g., cost, mass, power, schedule, volume, and risk budgets). A resource would be considered a reserve if it can be extracted and processed within the mission's constraints. This means that the definition of a reserve would be specific for each mission. We suggest that this direct linkage between missions and reserves is important to advance planning and implementation of specific lunar in-situ resource utilization (ISRU) activities.

Quantitative Lunar Resource Assessments: There are published estimates of the amounts of different lunar resources [e.g., 7]. While necessary and useful, these are not equivalent to quantitative resource assessments because they lack the rigorous estimates of uncertainties needed to calculate risk. What we propose is a framework that breaks the assessment into a series of generic steps. The analysis done within each step can vary from resource to resource while maintaining consistency in the scope of what is considered and the format of the output. This consistency would facilitate comparison of diverse ISRU concepts, especially architectures that rely on combining commodities from multiple resources.

Figure 1 illustrates this framework with each step of the assessment being called a "model." In the following, we very briefly note some of the key aspects of each of these models.

Geologic Model. The first step is a geologic model that describes the conditions that lead to deposits of the resource on the Moon. This is a prerequisite for further work because, without it, there is a real possibility of mixing data from fundamentally different types of

Figure 1. Schematic diagram of the proposed QLRA methodology



deposits which would invalidate the statistical methods used later in the assessment.

Spatial Model. This is a map of the locations (sometimes called "tracts") on the Moon that have conditions favorable for deposits of the resource. Actual deposits are not necessarily present within these tracts but deposits are not expected outside of them. Ice favorability maps [e.g., 8] are sophisticated examples of resource spatial models.

Deposit Number Density Model. This model is in the form of a probability mass function (PMF) for the predicted number of discrete deposits per unit area within favorable areas. This model is not needed when the resource is very widely distributed; for example, bulk regolith forms an essentially global layer.

Deposit Size/Quality Model. These are PMFs describing the amount of resource (often in units of mass) and the quality of the resource. In the language of terrestrial mineral resources, these would be called grade and tonnage models. The metric for the quality of the resource is different for each resource. For example, for ice it may be ice concentration while for solar energy it could be the longest time in shadow.

Technical Recoverability Model. There are multiple ways in which technical constraints on recoverability can be accounted for in a model. One consideration is the fraction of each tract that is accessible to extraction equipment. A different constraint could be the minimum quality of the deposit for a particular processing technique. It is essential that each constraint be provided as a quantitative metric with well-described uncertainties. This model can be skipped if the focus is on simply how much of the resource exists.

Statistical Model. The spatial, number density, size, quality, and recoverability models need to be combined rigorously. In practice, this is best done using numerical Monte Carlo methods [4]. The output are probability distributions for the amount of resource.

Report. The report needs to provide sufficient detail to be transparent with respect to assumptions, methods, limitations, data sources, etc., but also condense the results into a format that non-expert decisionmakers can use. The USGS's experience is that high-level decisions are driven by three values: (1) the most likely outcome, (2) a plausible worst-case, and (3) a best case that should be planned for. In many situations this can be provided as the median with 95% confidence limits. However, some projects may be willing to accept more or less risk than this and some situations require a more nuanced presentation of the distribution of possible outcomes.

Current Assessability of Lunar Resources: A key question is if the proposed QLRA methodology places unreasonable demands for input data. To investigate this, we considered six different resources, two each within the energy, minerals, and water categories. We find that the combination of remote sensing data, in situ data from the *Apollo* missions, and existing lunar samples are sufficient to follow the QLRA methodology for five out of the six resources (Table 1).

	Current Status (2022)
Solar Energy	Identified Recoverable Resource
^{3}He	Identified Unrecoverable Resource
Bulk Regolith	Identified Unrecoverable Resource
Regolith O_2	Identified Unrecoverable Resource
Bound H_2O/H	Identified Unrecoverable Resource
Ice	Undiscovered Resource

Table 1. Applicability of the QLRA methodology to six representative lunar resources with technology available in 2022.

The resource that lacks data essential for a QLRA is lunar ice. The critical gap is in situ data from the polar regions. NASA's *VIPER* mission will directly address this problem. It is a reasonable expectation that some types of ice deposits will prove simple enough to quantitatively assess after *VIPER,* but it is also plausible that some forms of ice will require additional investigation.

Assessments in Context: While important, resource assessments are just one part of the journey to the actual use of lunar resources. Of the six resources considered in Table 1, only one (solar energy) can be converted to a commodity (electrical power) with technology that is mature today. However, there are many efforts to develop extraction and processing capabilities for an array of lunar resources far broader than listed in Table 1. The question of which ISRU technologies should be prioritized would benefit from quantitative assessments of the relevant resources.

Especially for a sustainable human presence on the Moon, lunar resources will need to be managed ethically. The 2022 Lunar Surface Science Workshop on Inclusive Lunar Exploration [9] discussed many aspects of this, highlighting the fact that the Moon is important to cultures and peoples across the Earth. Quantitative lunar resource assessments would be integral to science-based management of lunar resources.

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