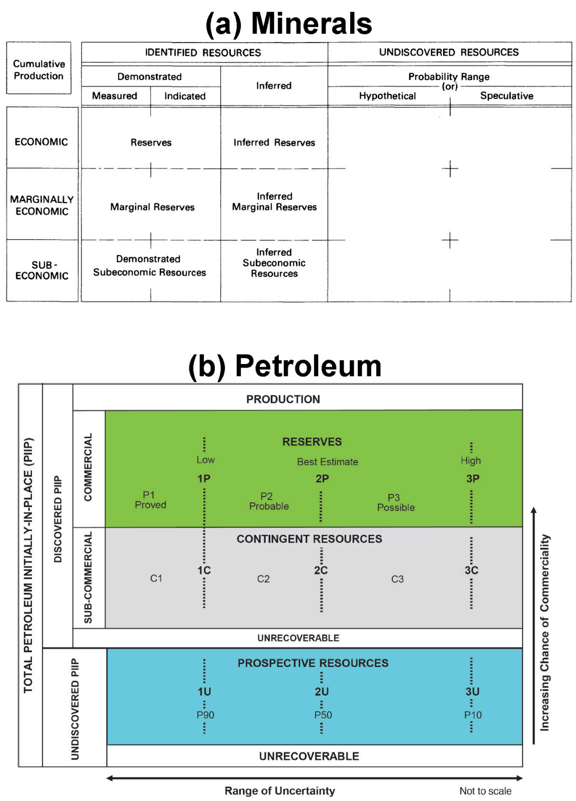
A SIMPLIFIED CLASSIFICATION SCHEME FOR LUNAR RESOURCES AND RESERVES. L. Keszthelyi[1] and J. Coyan[2], [1]U. S. Geological Survey, Astrogeology Science Center, Flagstaff, AZ 86001, USA (laz@usgs.gov), [2]U. S. Geological Survey, Geology, Minerals, Energy and Geophysics Science Center, Spokane, WA 99201, USA.

Introduction: The classification of natural resources on Earth uses a variety of different schema depending on the relevant disciplines (scientific and legal) [e.g., 1–3]. For example, different terms are used for resources versus reserves and for mineral versus energy resources (Fig. 1).

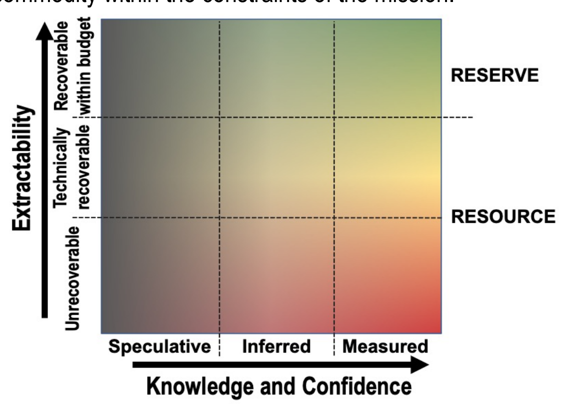
Figure 1. Two examples of terrestrial resource and reserve classification schemes. (a) from the U.S. Bureau of Mines and U.S. Geological Survey for minerals [1]. (b) from the Society of Petroleum Engineers for petroleum [2].



While there is some value in directly applying the terrestrial classifications to the Moon, there are reasons to seek simplification. First, the large number of overlapping terms can be confusing to lunar scientists and explorers. A single set of terms for the full panoply of lunar resources would be clearer and more readily adopted. Second, much of the terrestrial terminology is linked to legal and financial concepts that are not (yet) applicable to the Moon. A simpler scheme acknowledges this absence and may promote simpler and more consistent future legal language to be adopted for the Moon.

Proposed Classification: As with most terrestrial schemes, we propose to consider classification in two dimensions: (1) confidence in the knowledge about a deposit and (2) the ability to convert the resource into a useful commodity (Fig. 2). The UN Framework for Classification of Resources includes a third dimension: environmental/socio-economic viability [3]. This dimension should not be ignored for the Moon, but such considerations can be folded into the requirements to convert a resource into a commodity.

Figure 2. Proposed simplified classification scheme for generic lunar resources and reserves. *Speculative* is for resources for which only theoretical or remote observations exist. *Inferred* is for resources that have been investigated in situ, but not at the site in question. *Measured* indicates that detailed in situ data exist for the deposit that is to be utilized. To be a *reserve*, the resource can be converted into a useful commodity within the constraints of the mission.



To describe the confidence in our knowledge of a resource, we use the term "speculative" to mean there are theoretical and indirect reasons to expect deposits of the resource in the area, "inferred" to mean the properties of the deposits in the area are estimated by extrapolating from other well-studied regions, and "measured" to mean the properties of the deposits have been directly measured within the area being assessed. We adopt the concept of a "technically recoverable" resource that is used in assessments of petroleum resources on Earth. It was found that it was important to limit consideration of new technologies to those that are likely to be available for commercial-scale production in a 30-year timeframe [4], and we suggest that this translates well to discussions of lunar resources as well. In terms of the widely used Technical Readiness Levels (TRLs) defined by NASA, this 30-year timeframe can be translated as technologies that are currently at TRL3 or higher (that is, the concept has been proven to be viable at least in the laboratory). We use the term “unrecoverable” if we are unable to find public documentation of technology to convert the resource into a commodity at TRL3 or higher.

On Earth, the term “reserve” is limited to the portion of the resources that can be economically extracted [1]. For the Moon, we currently cannot rely on market forces to define what is economical. Instead, we propose that for a deposit to be considered a reserve, the conversion to a commodity must be achievable within mission constraints such as power, mass, volume, schedule, cost, and risk budgets. Typical space missions do not have sufficient risk budgets to consider speculative or inferred deposits as reserves. However, there are exceptions. For example, an in situ resource utilization (ISRU) technology demonstration mission may find it acceptable to go to a site that has only inferred deposits.

Application: The applicability of this simple classification to a wide variety of lunar resources is demonstrated by considering some specific energy, mineral, and water resources.

Table 1. Application of the proposed classification system to some diverse lunar resources.

Resource	Classification
Solar energy	Measured reserve
^3He	Measured unrecoverable resource?
Bulk regolith	Measured technically recoverable resource
Regolith oxygen	Measured technically recoverable resource
Bound $H/OH/H_2O$	Inferred technically recoverable resource
Water ice	Speculative unrecoverable resource

Solar energy. This resource is extremely well-understood that can be converted into a useful commodity (electrical power) with existing technology. Solar energy is planned to be used by multiple upcoming missions, including PRIME-1 and VIPER. This makes solar energy a measured reserve for most lunar missions.

Helium-3. It has been suggested that ^3He from the Moon could be used to power fusion reactors. However, it is unclear that such reactors will be available on a commercial scale within the next 30 years [5]. Therefore, it is debatable if ^3He meets the criteria to be considered a resource. Furthermore, harvesting ^3He from lunar regolith has not been demonstrated, so it would be an *unrecoverable* resource. At the same time, Apollo samples confirm that ^3He is indeed found disseminated across the Moon [6], so ^3He is a *measured* resource (if it is a resource).

Regolith. A number of studies demonstrate that lunar regolith could be used to construct useful structures such as landing pads, roadways, and habitats. Other experiments have demonstrated how oxygen can be extracted from the regolith. The lunar regolith is effectively a single global deposit, which we have sampled and measured in many locations [7]. While there are differences between the regolith on the mare lavas and the feldspathic highlands, these are well-understood and regolith properties can be predicted across the Moon with high confidence. Within a 30-year timeframe, regolith appears to be a *measured technically recoverable* resource for both construction and oxygen.

Hydrogen/hydroxyl/water bound to regolith. There are also a number of in situ, remote sensing, and sample analysis studies that show that hydrogen is bound to lunar regolith as various chemical species (especially OH and H_2O). However, these studies suggest that the nature and quantity of this bound hydrogen have considerable variability, variability that is not yet predictable [8]. Recovery of bound hydrogen-bearing molecules by heating the regolith has been demonstrated in the laboratory [9]. Thus, hydrogen bound to the regolith can be considered an *inferred technically recoverable* resource.

Ice. There are strong theoretical reasons to expect ice in cold traps on the Moon and remote sensing data indirectly supports the presence of water ice. The one direct measurement from LCROSS seems to confirm the presence of water in at least one location, but the formal uncertainties on this detection are considerable [10]. Given that we do not know the quantity or nature of the ice, it is not possible to demonstrate recovery methods. As such, lunar water ice needs to be classified as a *speculative unrecoverable resource*. However, the upcoming NASA VIPER mission will address many of these issues. It is plausible that ice will be an inferred recoverable resource in a few years.

References: [1] U.S. Bureau of Mines and U.S. Geological Survey (1980) *USGS Circular 831*, https://doi.org/10.3133/cir831. [2] Society of Petroleum Engineering (2018), https://www.spe.org/en/industry/petroleum-resources-management-system-2018/. [3] United Nations Economic Commission for Europe (2019) *ECE Energy Series, 61*. [4] Schmoker, J.W., and Klett, T.R., (2005) *USGS Digital Data Series* DSS-69-D. [5] Temmerman, G.D. (2021) *Joule*, *5*, 1312-1315. [6] Wittenberg, L.J,. et al. (1986) *Fusion Technol., 10*, 167 –178. [7] Heiken, G., et al. (1991) Lunar Sourcebook: A User’s Guide to the Moon. [8] Lucey, P.G., et al. (2022) Geochemistry, 82, https://doi.org/10.1016/j.chemer.2021.125858 [9] Hibbits, C.A., et al. (2011) *Icarus, 213*, 64-72. [10] Colaprete, A., et al. (2010) *Science, 330*, 463-468.