ANALYSIS AND ECONOMICS OF EMERGING SPACE INDUSTRY: LUNAR RESOURCE EXTRACTION. A.J. Gemer[1], B. Seifert[2], S.A. Szatkowski [3], and J. Thomas [2], [1]Laboratory for Atmospheric and Space Physics (1234 Innovation Drive, Boulder CO 80303, Andrew.Gemer@lasp.colorado.edu), [2]Advanced Space (2100 Central Ave #102, Boulder CO 80301, seifert@advancedspace.com, james.thomas@advancedspace.com), [3]United Launch Alliance (9501 E. Panorama Cir, Centennial CO 80112, Scot.A.Szatkowski@ulalaunch.com).

Introduction: The extraction of water from the lunar surface is not only economically viable, but a necessary step to enable the future of space development. Lunar water extraction will serve to spur technological, operational, and policy development, and will pave the way for in-space utilization of other material resources as well. Prospecting, accessing, and utilizing this water is a critical and economically-viable step to creating new space capabilities and extending mankind's presence in space.

Lunar Resource Extraction Economy: According to recent studies, upwards of 600 million cubic meters of water ice exists in permanently-shadowed craters at the lunar poles, occurring in concentrations as high as 90-100% [1]. While the craters are permanently shadowed, the crate rims see nearly constant sunlight (100% at the north pole and 98% at the south pole), allowing effective collection of solar energy to power water extraction activities. Obtaining water in space and using it as spacecraft fuel (in the form of LH2/LOX) makes a host of new space operations possible, including in-space refueling and sustained manned exploration beyond Low Earth Orbit (LEO), while decreasing the costs associated with space transportation, making space more accessible to a worldwide market.

The Gross Space Product (GSP), a measurement of global space activity including commercial infrastructure and support industries, commercial space products and services, and government space expenditures, had a value of $330 billion USD in 2014 [2]. This is based on the current industry paradigm of expendable launch vehicles, leading to a high cost of launch to orbit and creating a barrier to space access while limiting the demand for launch services. A shift to distributed lift capabilities and reusable/refuelable upper stages for in-space transport will create a new market for water and rocket fuel in space, providing an economic incentive for lunar water extraction and increasing the volume of space traffic. These distributed lift concepts allow for enhanced delivery efficiency and/or direct injection of Earth-orbiting satellites.

Early customers of this lunar water will be space transportation companies interested in developing reusable/refuelable rocket upper stages; for instance, United Launch Alliance has announced its Advanced Cryogenic Evolved Stage (ACES), capable of transporting, transferring, and storing fuel in space [3]. NASA and other governmental spaceflight entities will also be early customers, with lunar water providing life support and radiation protection for crewed habitats and enabling both manned and robotic exploration of Mars and deep-space missions.

With the current expendable launch vehicle paradigm, the cost to transport a kilogram of water, fuel, or payload from the Earth's surface to LEO is about $4k, $16k/kg to GSO, and $35k/kg to the lunar surface. If water (or fuel) could be produced at the lunar surface for $500/kg and transported to LEO, it could serve as a cost-competitive substitute for Earth-launched resources. Our studies indicate that initial demand for fuel derived from lunar water at LEO will be about 200 MT, requiring the extraction and processing of 1500 MT of water on the lunar surface. This process would require 40 MT of infrastructure to harvest that amount of water at $50k/kg to build and $35k/kg to launch to the lunar surface, using 10-15 traditional launches. Thus, the infrastructure cost per kilogram of water/fuel produced is $85k/kg, requiring a $4 billion initial investment and realizing initial revenues of $500 million per year.

In addition to the economic incentives, a mission to extract water from the Moon will serve to advance technologies critical to future space development, such as fuel transfer, rendezvous, and docking systems, surface activities (both manned and robotic), and in-space manufacturing. Launch, infrastructure, and hardware suppliers will see increased demand for their products and services, and many are already standing by to provide support for this type of mission; an example is Masten Space Systems and their XEUS large lunar lander system [4]. Data collection and remote sensing suppliers will also see new applications for their products and services in this new space economy. These technologies are both necessary and complementary to the development of lunar resource extraction, and will serve to spur additional growth in the GSP. In the next 30 years, the GSP will stretch into the trillions of dollars, kick-started by lunar water extraction and bolstered by the aforementioned developments.

Once the lunar resource extraction economy has been initiated by use of lunar-derived water and fuel, a wide variety of other space activities will be enabled. These include the development and testing of manned lunar habitats and communications infrastructure that will be beneficial to future Mars exploration missions. Space tourism will play a significant role in this economy, both as a customer of lunar-derived fuel water and fuel and using the Moon as a space-tourist destination. Scientific research will also greatly benefit from the increased access and decreased cost of space exploration, as well as from access to data and samples obtained during lunar prospecting. Finally, developing technologies to manufacture structures in space from local raw materials, rather than using structures manufactured and launched from Earth, will allow the construction of previously impossible large space structures for a wide variety of purposes.

Policies & Regulation: The main goal of the government, regardless of what role(s) it may play, should be to assist in the establishment and maintenance of the economic viability of lunar resource extraction. To ensure regulatory clarity and maintain market stability and fair access, some form of government (likely an international coalition) with special jurisdiction over the areas intrinsic to lunar resource extraction operations needs to be established. Actions taken (or not taken) by the government on both national and international scales significantly influence business activities and economic behaviors across entire industries. The lunar resource extraction and utilization market will be strongly influenced by how the government behaves in its different roles as supplier, customer, competitor, regulator, and investor.

Challenges: A number of economic and technical challenges must be overcome to facilitate the establishment of this emerging space economy. The initial investments in infrastructure and delivery are significant, and must be amortized to reduce the unit costs of fuel to a reasonable price. The timelines for development of necessary technologies and funding of this development will significantly influence the viability and timeline of the industry. Technical challenges, such as high-resolution lunar prospecting, the lifetime of machinery in the lunar environment, energy access in permanently-shadowed crater regions, and processing and storage of lunar water must be met. In addition, the changing priorities and policies and long-term stability of customers influences the stability of the market, impacting the long-term growth rate of this economy.

Competitors to this new space economy will primarily be from Earth-sourced suppliers in the early stages of development. An important trend to note is that reusable launch vehicles and other launch improvements will both lower the cost of infrastructure on the Moon and lower the added value of lunar resources to Earth orbits. In the future, improvements in non-LH2/LOX-based in-space propulsion such as electric propulsion may serve as a competitor to lunar resource extraction, as would resources obtained from Near-Earth objects (NEOs).

Conclusions: Establishing a new space economy is necessary to extend mankind's reach into space, and will enable a new generation of space research and exploration. The utilization of resources already in space is a critical part of this economy, and the technology, infrastructure, and policy necessary to enable this economy may be developed for applications to the extraction of water from the lunar surface. A compelling business case for these types of missions can be made by examining trends in launch vehicle development (reusable vehicles, distributed lift), where the use of lunar-derived fuels provides competitive and enabling advantages over Earth-derived consumables. Lunar water extraction serves as a low-hanging fruit to kick-start a new space economy, which will eventually include a wide array of systems that will enable mankind to both utilize cislunar space more effectively as well as to expand to more distant space destinations.

References: [1] Spudis, P. D., & Lavoie, A. R. (2011). *Using the resources of the Moon to create a permanent, cislunar space faring system.* AIAA SPACE 2011 Conference & Exposition [2] Space Foundation (2016) *The Space Report 2015*. Retrieved from www.spacefoundation.org. [3] Barr, J. *ACES Stage Concept: Higher Performance, New Capabilities, at a Lower Recurring Cost.* AIAA SPACE 2015 Conference & Exposition. [4] Scotkin, J., Masten, D., et. al. *Experimental Enhanced Upper Stage (XEUS): An affordable large lander system.* Aerospace Conference, 2013 IEEE, Big Sky, MT, 2013. Pp.1-9.