Space Resources Commodities Exchange

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ABSTRACT
In recent years, a new opportunity has evolved with the discovery of water on the Moon and a new vibrant entrepreneurial approach to space exploration. The development of space will require significant amounts of resources to support the growth of this new economy. A space resources commodities exchange (SpRCEx) could exist to facilitate transactions of these resources. For companies wishing to compete in space, a commodities exchange offers meaningful value in the form of risk mitigation for market participants buying and selling to/from the exchange. Further, marketplace services such as resource storage and data and listings provide exchange owners a revenue stream uncorrelated to trade volume, thereby reducing operational risk. Although it is not currently feasible to establish an SpRCEx, this study focuses on the development and execution of a dedicated exchange assuming certain conditions are met. After identifying these critical assumptions, primarily the stable supply of at least one space resource, and the presence of significant market participation and trade volume, the authors conclude that a dedicated exchange offers relative value for all market participants, including buyers, sellers, speculators, and owners.

Keywords: space resources, commodities exchange, rocket propellant, *in situ* resource utilization

BACKGROUND AND INTRODUCTION
Space exploration is in a new era where private entities are entering the field, which was previously the exclusive domain of government enterprises with associated contractors providing specific, custom deliverables. In addition, aerospace technology, which was mostly initiated in the 1950s and 1960s with government funding and guidance, has become democratized and more economical through the development and implementation of new technologies such as advanced computers and related software systems. An entire space technological eco-system has evolved, coupled with emerging information technology enablers that are providing efficiency multipliers through better flow of information and access to research efforts with collaborative potential. An example is the Earth remote-sensing industry, where large and expensive government satellites are being supplemented and, in some cases, replaced by smaller, cheaper "cubesats." This has led to the formation of entrepreneurial startup companies that have attracted significant investment and new business models, such as Planet, Orbital Insight, Astro Digital, Space Know, Geosys, and more.[1]

As space technologies become more mature, there is a trend toward standardization and commodification. By ensuring definition and quality of goods and services, there can be a business advantage leading to increased economic activity. When standards for cubesats were introduced and adopted, a supply chain evolved, which enabled the new remote-sensing industry that is evolving today. Interfaces are particularly important in this aspect since they allow interoperability between various competitors' products and can promote safety and flexibility (*e.g.*, common airlock docking mechanisms, power outlet interfaces, metric system for design, quick disconnect coupler fittings for fluids, pneumatics, power, and data flow exchange).

In this study, space resource commodities have been researched, defined, and evaluated as enablers for a Cislunar solar system economy. The establishment of a Space Resources Commodities Exchange (SpRCEx) could be the key component for enabling a more rapid adoption of space resources concurrent with complementary technology development. This study examines the potential merits and feasibility of such an exchange assuming that the following criteria have been established. All criteria are critical for any resource to be treated as a commodity and in justification of the existence of an exchange. A commodities exchange exists and operates around space resources. This study has assumed SpRCEx to be that exchange.

- A standard for water quality used in commodity trading exists. This study has assumed the International Standards Organization (ISO) 3696 to be that standard.
- There are multiple sources of water, where at least one is not from Earth.
- There is a commercial demand for water in space.

There are historical precedents for commodities trading exchanges on Earth, and these well-developed commodity

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trading models and business methods can be applied to a case study to test the applicability of such economic activity. Commodity markets date back to Ancient Greek and Roman times where grain and its seasonal growth, quality, place of harvest, and supply routes led to government price controls, duties, and regulations.[2] Since 1531, when the Antwerp Bourse was opened for the trading of commodity and financial futures, various other commodity exchanges have developed, for commodities such as: agricultural, metals, minerals, energy, environmental emission, foreign currency exchange, freight and transportation services, weather risks, and financial futures related to such.

Can space resources be commoditized and can this result in a beneficial space resources commodity exchange? This study critically examines these questions and presents relevant observations and conclusions based on existing literature, and the knowledge of subject matter experts.

Commodity Definition

Commodities are defined as mined, manufactured, or grown goods or services that are unspecialized.[3] It is important to note the word "unspecialized" in the definition. To be considered a commodity, goods or services must be interchangeable with other similar goods or services. A good example that illustrates the difference between specialized and un-specialized goods is the difference between copper and wrist watches. Copper cathodes are interchangeable from other copper cathodes. Assuming certain purity standards are met, there is little to differentiate 1 kg of copper from the next. Wrist watches, however, show hardly any uniformity. Copper cathodes are a commodity and watches are not.

The definition just cited outlines a very general rule for commodities. It is important to also consider that defining a good as a commodity implies adherence to certain quality standards. These standards can be form, phase, composition, or location:

- Form—The term "commodity" implies a certain form. Typically, this is a shape and/or weight. Metal commodities are sold in ingots by weight. This standard is somewhat loosely applied and is mostly a result of the practical limitation of moving and storing goods. As an example, 1 metric ton increments are easily movable; 10,000 metric ton increments are not.
- Phase—Commodities usually reside in the same phase as other goods in the commodity class. This helps promote interchangeability of the goods, which is required for a good to be a commodity. An example of this is crude oil. Crude oil is sold as a liquid and is not traded as a commodity in gaseous or solid form.
- Composition—Composition may be the most important aspect of a commodity, and it can be interpreted as a purity standard. Metals are sold on the basis of purity and impurities may incur price penalties or, if the impurity levels are high enough, the metal may not qualify as a commodity.
- Location—When buying or selling material, location is important. Most commodities have the potential to incur significant shipping costs if they are required at a different location. Commodities transactions typically specify a location for delivery.

For the sake of simplicity, the authors of this work have chosen to focus on the commodity of water in space. Water is a critical material in the development of space; as noted by "The Economist" magazine: "Our lives, literally, depend on [commodities]"[4] which makes water the perfect example commodity in this case. It is necessary to sustain life and it is a fuel and oxidizer precursor for propellants that can provide mobility. The focus of this work is water for use as a propellant in space. The standards for the commodity of water in space are:

- Form—1-ton increments
- Phase—liquid
- Composition/Purity—Meets ISO 3696 Grade 2
- Location—Earth Moon Lagrange (EML) point 1

The authors note that the range of potential commodities in space is quite large. Although this work focuses on water, a list of potential commodities is presented next. Once a commodities exchange is operational, these commodities may also begin to trade on the exchange:

- Power
- Solar panels for power generation
- Regolith and derived feedstocks
- Manufactured goods—along the lines of structural members for habitat construction (if standardized)
- Cargo capacity—for moving material around
- Etc. (Market-driven demand based)

Commodities Exchange

Commodification transforms physical goods and services into standardized contracts and turns capital today into contractual rights for delivery of goods in the future. The complexity of creating modern technology requires a reliable supply of graded materials and components for use in manufacturing. A commodities exchange facilitates this by setting the price, quality, and terms for trade and delivery of physical commodities, and the derivative products that depend on them. The resulting standardization is a catalyst for economic growth by encouraging natural economies of scale.

Entities all over the world buy and sell commodities from/to one another. If this activity is done through a third-party marketplace, the marketplace is a commodities exchange. An analysis of the 2 pre-eminent financial exchanges, the Intercontinental Exchange (ICE) and the Chicago Mercantile Exchange (CME), offers relevant insight into the operation of the SpRCEx. In a derivatives market trade, exchanges earn transaction and clearing revenues from both counterparties to each contract. More than 90% of exchange volume is through electronic trading, so the core revenue driver for both exchanges is electronic trading fees.[5] With fees assessed on a per-contract basis, revenues fluctuate with changes in contract volume. Rates charged per contract vary with market conditions, product type, and overall volume, among other factors.

Importantly, the ICE and CME own and operate internal clearing houses to confirm and settle each trade, so the revenue generated by clearing is attributable to each exchange. An alternative solution is to outsource clearing and settlement to an established platform, a strategy recently implemented by Africa's largest exchange, the Johannesburg Stock Exchange (JSE). Rather than developing and operating an internal clearing house, the JSE partnered with Cinnober, a real-time clearing platform recently acquired by Nasdaq.[6] As the early stages of the SpRCEx will involve limited trading volume, establishing an internal clearing house offers little benefit relative to the cost of development. With modern clearing requirements and the evolving regulatory landscape needing significant investment in technology, partnering with a clearing platform offers reduced up-front costs and operational complexity for the SpRCEx.

The ICE and CME also provide subscription-based data services to their clients, earning revenue from pricing and reference data on hard-to-value financial instruments. Data services are used by clients to inform risk management, support regulatory and compliance needs, and improve operational efficiency. The ICE draws in significantly more from data services as a proportion of total revenue (42% in fiscal 2018) than the CME (10%), with the discrepancy due to CME's relative lag in development.[5] As of 2016, CME Data Services was shipping physical hard drives off manual extracts from their data warehouse, though efforts are being actively taken to reconcile the underperformance.[7] A clear trend moving forward is client appetite to work directly with exchanges for data acquisition, thereby consolidating data sources and reducing overall costs. The SpRCEx will be uniquely positioned to capitalize on data service offerings. As the first widely accepted exchange for space resources, it will establish industry-wide standards for valuing space commodities and standardizing risk transfer vehicles. Without incumbent exchanges to compete with, customers will pay a premium for access to SpRCEx data sets, pricing support, and network.

Financial Instruments and Financial Engineering

With a commodities market comes the potential for the creation of financial instruments through the art of financial engineering. If sufficient volume is present on a commodity exchange, it becomes possible for market participants to create instruments that seek profit and transfer risk by exploiting delivery timing differences on the exchange. A number of these instruments are outlined next:

- Futures Contracts—"A futures contract is an agreement to buy or sell a predetermined amount of a commodity at a specific price on a specific date."
- Call Options—"Contracts that give the option buyer the right, but not the obligation, to buy a commodity at a specified price within a specific time period."
- Put Options—"Contracts that give the option owner the right, but not the obligation, to sell a specified amount of a commodity at a predetermined price within a specified time frame."[8]

These instruments allow for market participants to either seek profit via exploitation of market price movement or engage in risk mitigation by exploiting market availability. Often, these 2 motivations are likely to reside on opposite sides of the same financial instrument. For example, a seller or producer may decide to sell a call option over future production with a 6-month term at a price that reflects a slight premium to the current market price. For creating the call option, the seller receives a fee. If the price fails to rise above the call option strike price, the option will expire unexercised and the seller will not be forced to fulfill the call option, while still earning additional income from the call option fee. If the price increases substantially, the holder of the call option will exercise the option and buy the material specified in the contract for less than the market price. This results in a benefit to the option buyer but a loss to the option seller.

It is important to note that these instruments can be used alongside one another to engineer an outcome. A good example of this is a zero-cost collar. In this simplified example, an option to buy material at a slight premium to market is purchased alongside an option to sell the same material at a slight discount to the market. In conjunction, these options are used to define a narrow range of experienced commodity prices and control the market participants' exposure to market price risk.

In the context of space resources development, risk mitigation for market participants offers a significant benefit.

Establishing a commodities exchange for water will allow suppliers to ensure price stability for their product through the use of future contracts and options. Rather than spending resources on forecasting future cash flows, producers can focus on efficiency in production. The same instruments afford product buyers protection from market price volatility, making it easier to plan and budget operating margins.

Space Resources

"Space Resources" is a general term that refers to the potential locations, materials, elements, and energy sources that may be utilized in the exploration and development of space. For this study, space resources are considered to be solid, liquid, or gaseous substances that have economic value. This narrowing of the generic term is specific to this proposal, in that the focus of the proposal is to evaluate the potential for the existence of and use cases for a space resources-focused commodities exchange. In short, the term "space resources" is being confined to extractable and tradeable physical commodities in Cislunar space.

Terrestrially, the commodification of components made by highly specialized enterprises enabled the rise of standardized chipsets, routers, cameras, programming languages, and other technological assets that are adaptable to an infinite variety of uses. In addition, the risk transfer derivatives reduce insurance costs and enhance the creditworthiness of participants, while attracting speculators to provide liquidity in the market. However, the strategic opportunity offered by controlling the supply chain of precious commodities does not come without conflict. For example, China's Shanghai Futures Exchange (SHFE) has steadily increased influence over the supply and demand for precious metals and other commodities used in electronics, manufacturing, and other industries. By lowering transaction fees, adopting accommodative regulatory procedures, and denominating trades in domestic currency, SHFE is positioned to challenge incumbent global commodities exchanges, such as the CME and ICE.[3]

As it relates to space, an SpRCEx would add robust supply, demand, interoperability, transparency, and risk transfer capacities to support the space economy. Lunar water, for example, is poised to be one of the first space commodities. Since its use as an industrial rocket fuel[25] and oxidizer would differ in quality and quantity from that intended for human consumption, commodification permits a standard unit of quality (ISO 3696/2), which is the water quality required by a typical proton exchange membrane (PEM) electrolyzer, and quantity for use in a specific destination for a defined period.[3] In addition, the financial derivatives traded on an SpRCEx would attract liquidity and diversify risk for the space economy, enabling the viability of commercial space business models. Given the increasing role and dominance of commodities exchanges in China, an SpRCEx organized in the United States could also serve as a means for minimizing resource constraints on U.S. interests terrestrially and in space. The SpRCEx would bring interoperable standards and assure a consistent quantity and quality of space commodities that are critical to the supply chains, supporting commercial and national security interests in space.

Examples of space resources commodities. Space resources as commodities can equate to almost all commodities exchanged on Earth; if a high demand exists for a material or service found or operated in space, respectively, and quality and risk can be standardized, then it could be considered a commodity. Further, as new materials are discovered or needed in space, the compendium of space commodities will grow.

With what is known to exist and have a known demand, space commodities can be categorized into *Raw Materials*, *Processed or Refined Goods*, *Services*, *Contractual Rights*, and *Financial Rights*. These 5 categories, as defined by Cahan *et al.*,[2] are summarized in *Table 1*.

The first resource that will be treated as a commodity will be water, a *Raw Material* or *Processes Good*. As a commodity, an exchange does not care where the commodity originates from and thus it could be launched into space from Earth or processed *in situ* on the lunar surface or other celestial bodies. With many uses, such as for life support, plant growth, space radiation shielding, cleaning, washing, hygiene, industrial processes, and extracting hydrogen and oxygen, water will be in very high demand with many available sellers. The first of those demands will be a water-based rocket propellant.[25] Rocket propellant requires purified and deionized water meeting (ISO) 15859-10.[9] An electrolyzer requires higher purity deionized water meeting (ISO) 3696 Grade 2. This purity of water is a characteristic that can be standardized and verified through an exchange. It is unlikely, however, that the cryogenic propellant itself will be considered a commodity, because it is difficult and expensive to transport, requiring pressurized and insulated vessels; it is cheaper and easier to produce at the EML-1 depot through electrolysis, using free and abundant solar energy; and it requires the seller to convert the water into fuel, making it harder to measure and guarantee grade by the exchange.

Space Resource Utilization Plan

- *Goal:* Establish a commodities exchange for space resources

Table 1. Examples of Space Commodities

Space Commodity Category	Examples
Raw Materials	Regolith, rock, mineral, or natural substance
Processed Goods	Naturally occurring process such as biological or agricultural plant, food, waste-repurposing/waste-to-energy, or other process
	Human-engineered process such as producing water from lunar rock or hydrogen from lunar water
In-Space Services	Human-engineered processes for:
	Launch or other transportation to move cargo or personnel to or from space
	Robotic exploration or repair of in-space assets or objects
	Temporary physical storage or habitation with life support services
	Energy, telecommunications bandwidth, computational services for acquisition, storage, analysis, and manipulation of data (Information and Communication Technologies [ICT])
Contractual Rights	Spot, Future, and Forward Contracts to own or take physical delivery of another space commodity
Financial Rights	Future, Forward, Derivative and other contracts transferring the right to participate in changes in value of another space commodity

- *Resource:* Water
  - Propulsion (primary use)
  - Radiation shielding
  - Electrical power storage using solar panels and regenerative fuel cells
  - Life support
- *Technology:* Marketplace and Financial Engineering, Interfaces and transfer technologies, On-orbit depot storage, and On-demand electrolysis
- *Customers:* Space Transportation, Mining and Processing Companies, Speculators, Investors, Astronauts, and Settler

CASE STUDY—JET FUEL AND ROCKET PROPELLANT

In the case study to follow, we perform an analysis of an existing terrestrial market exchange and extrapolate how similar principles and practices would apply to a space exchange—for one commodity. We have identified water, primarily for use as a propellant in space, as the first commercially viable commodity offered by the SpRCEx. With similarity in market participants, the terrestrial airline industry provides a useful analog.

Fuel Hedging

For terrestrial airlines, fuel costs are a significant but highly variable expense, constituting 23.5% of total expenditure in 2018.[10,23,24] To manage fuel price risk, airlines purchase hedging contracts through a commodities exchange. Since other expenses are less volatile than fuel, airlines hedge to lock in the price of future fuel purchases, thereby stabilizing total costs, cash flows, and profits. Without hedging, airlines are exposed to significant volatility in fuel prices, negatively impacting customers and investors.

Most commonly utilized are futures contracts, which grant the right to deliver a standardized quantity of fuel at an agreed price on a fixed date in the future. Future positions are offset before expiration so that no physical delivery takes place; in fact, <1% of trades result in the delivery of the underlying commodity.[11] Airlines purchase fuel for day-to-day operations as needed at the market price, with the future cash flow offsetting the rising operational fuel costs. Each futures contract for fuel is standardized to 1,000 barrels, with assured quality of the product. Fuel hedging may extend 2 years in the future; however, the liquidity for contracts beyond 1 year ahead declines significantly.

Swaps, another applicable hedging option, are futures contracts whereby an airline will exchange payments at a future date based on the fuel price at that time. For example, an airline buys a swap for 1 month at a stated strike price for a specified amount of jet fuel. On expiration, the airline pays or receives the difference between the average market price for that month and the strike price. So, the market price of a swap is a monthly average rather than the price on expiration, such as a traditional futures contract.

As there are no exchange-traded futures available in aviation fuel, airlines use fuel hedging contracts denominated in crude oil. Crude oil is a strongly correlated product with a highly liquid market, eliminating the need for over-the-counter agreements between 2 parties, with the purchaser bearing full counterparty risk. Similarly, the derivatives market for in-space fuel will differentiate contracts depending on the propulsion type. Since the supply constraints, and therefore price action, vary significantly between propellant type, the SpRCEx will offer different contracts for water-derived LO2/LH2 than Xenon for ion propulsion, a possible future commodity.

United Launch Alliance Case Study—Failure to Deliver

This case study will discuss a scenario in which United Launch Alliance (ULA) is operating in a direct-transaction Cislunar economy. Figure 1 illustrates potential price points for this case study. In this scenario, the market is not utilizing a commodities exchange. Assume ULA is running a bi-weekly trip from Low Earth Orbit (LEO) to EML-1. The missions are supplied from water mined and processed *in situ* from the moon. The ULA has only 2 suppliers that chose to deliver the water to ULA at EML-1 a week before the beginning of each cycle.

- EML-1 Is chosen as point of delivery for the lower cost of delivery, because there is a significant cost benefit. The ULA has contracts to buy 1 kg of water for $1,000/kg, compared with $3,000/kg price point in LEO.[12]
- Company A makes bi-weekly deliveries of 5t of water at $1,000, totaling $5 million. However, they experienced technical difficulties in a transport of water this week and cannot fulfill delivery.
- Company B has a same contract to deliver 5t of water bi-weekly to EML-1; however, they have problems with their processing facility this week and cannot make delivery.

To mitigate counterparty risk, ULA operates a storage facility in EML-1 with 5t of propellant in case these situations arise. However, the ULA still needs 5t of water to complete their scheduled bi-weekly trip. The ULA must now seek out other suppliers; however, these companies may not have ample supply. Understanding the scale of ULA's demand, prospective providers will leverage their existing supply or steeply increase supply in accordance with ULA's needs. The cost of shipping their own water from Earth to EML-1 is $12,000/kg, which equates to $60,000,000.[12]

The ULA decides that an additional $55,000,000 is not economical and will postpone flight operation this week. As a result, ULA's customers cannot fly and new arrangements are needed for the future. With limited substitutes for transportation, the aggregate loss of value includes all customers that are reliant on ULA's cancelled service. In a highly interdependent value chain, the counterparty risk in direct transfers has implications that are far beyond the originating parties.

Instead, assume a vibrant market for water in space facilitated by the SpRCEx. Rather than bespoke agreements for direct transfer, the SpRCEx would offer standardized contracts to ensure the price, time, and location of physical delivery, or to offset variable cash flows. With a biweekly demand for $10 million of water, 1 option for ULA is the purchase of futures contracts. To satisfy monthly demand, ULA will purchase futures for water in aggregate of $20 million, at a market price of $1,000/kg. The contract grants ULA the right to receive 20t of graded water at EML-1 on expiration, at a fixed price of $1,000/kg. On the news that Companies A and B are facing supply constraints, the market price of water will spike. In our simplified scenario, the only alternative supply at this time must be sourced from Earth and delivered to EML-1 at a market price of $12,000/kg. As a result, ULA will sell back their futures position at the market price on expiration, which is $12,000/kg of water. The margin earned on their futures contract offsets the increase in market price, and ULA can purchase Earth-sourced water without impact to net cost.

Ultimately, the same economic rationale underpinning an airline fuel hedge applies to space transportation providers, ULA, or otherwise. The use of financial derivatives is to reduce fuel price risk, not to improve profits. The expected return on fuel hedging is 0. The value lies in cash flow stability, without which customers and investors would bear the risk of fuel price volatility. For emerging space ventures, cash flow stability is vital to attract investment and to sustain operations. With the high technical risk inherent in space activity, mitigating price volatility through SpRCEx derivatives offers substantial value.

SPACE RESOURCES COMMODITIES EXCHANGE

When beginning the research characterized in this article, it was hypothesized that a rocket propellant would be the first resource treated as a commodity by SpRCEx; however, the case study and further research has shown that deionized water will actually be the first commodity. As described in the case study, crude oil is the resource that airlines hedge and is treated as a commodity by exchanges. Crude oil is then refined into jet fuel and purchased outside the exchange. The same will be true with a water-based rocket propellant. Water will be hedged and treated as a commodity, and the buyers will process it into a rocket propellant. The SpRCEx will be established when water is in bountiful supply and would benefit from treatment as a commodity.

Conditions Required for Viability

Thus far, our article focuses on how an existing SpRCEx may benefit buyers, sellers, and speculators in the market for space resources. For market participants, a dedicated SpRCEx offers value under the following conditions: (1) a stable supply of at least one resource, and (2) at least 2 entities interested in purchasing said resource. A privately operated SpRCEx, however, will need substantial profit margins to justify establishment and operation. Traditionally, a commodities exchange is established reactively to address inefficiencies in an increasingly crowded market for raw and processed goods. The subsequent commoditization of services, contractual rights, and financial rights is enabled by the underlying market in physical commodities. An exchange generates income by transaction fees and selling data services, with

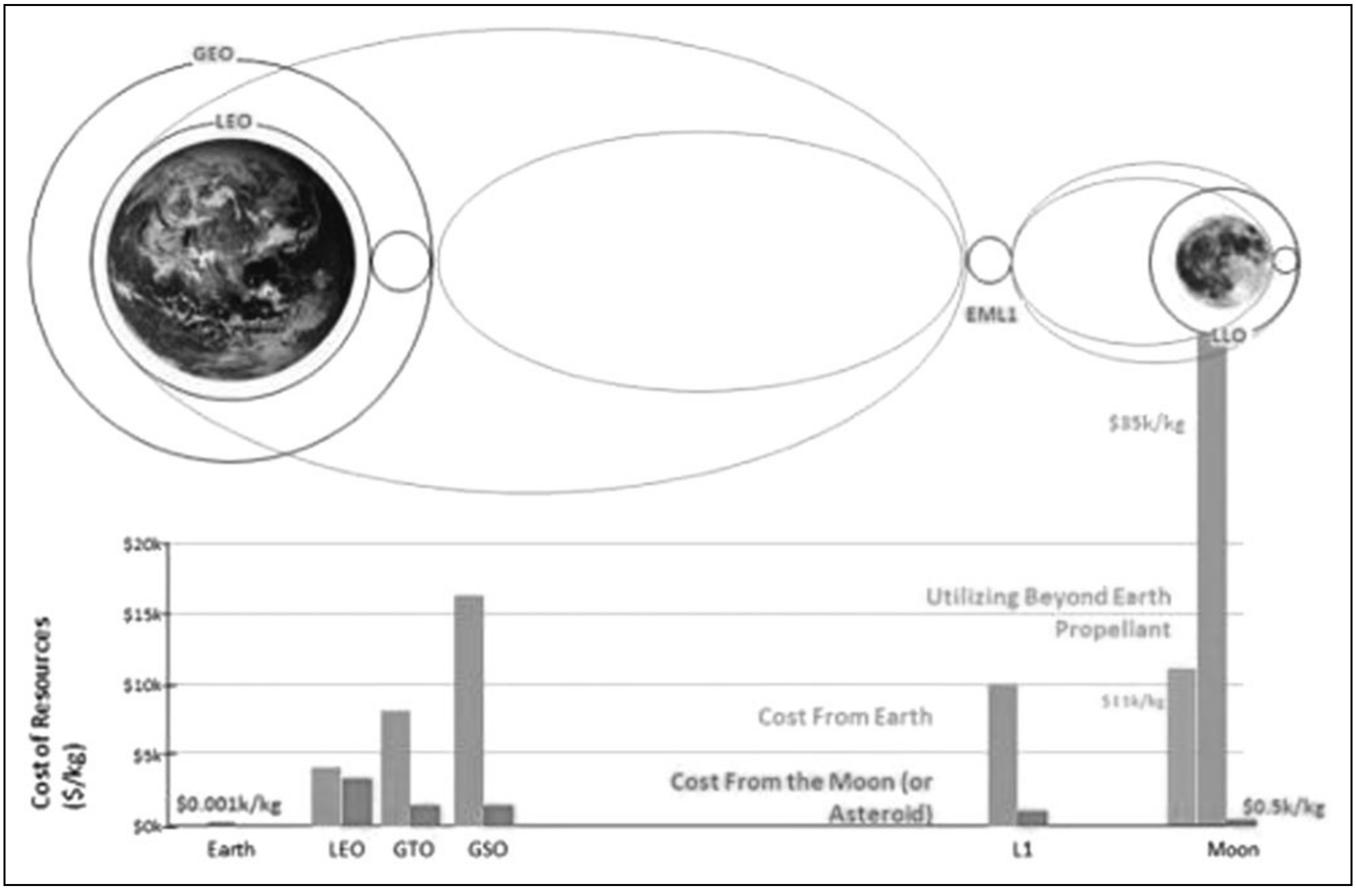

Fig. 1. Visualization of orbital locations and the potential price points based on lunar product versus Earth product.[12] EML, Earth Moon Lagrange; GSO, Geosynchronous Orbit; GTO, Geostationary Transfer Orbit; LEO, Low Earth Orbit.

revenue potential strongly correlated to market participation. For the SpRCEx, without an existing market in raw and processed materials for use in space, revenues generated from trading are not sufficient for exchange viability.

With a vibrant market for water in space several years away, how might the SpRCEx act proactively to add value in the interim? Assume we broaden the definition of a space commodity to a readily exchangeable item that has value to trading partners. By eliminating the need for an underlying physical good, the SpRCEx offers nearer-term value to the space economy.

Timeline

Figure 2 is an estimated timeline for establishing an SpRCEx. The timeline illustrates 4 potential milestones for an exchange to establish itself and increase near-term value and revenue.

Viable as early as 2025, SpRCEx could conduct business by offering data and listing services for global launch services to LEO. It is important to note that the commodity is not the launch itself, but rather a futures contract for establishing a launch within a set period (days). Just like commodity hedging, these futures could be considered risk transfers where the launch window fluctuates instead of the price. In the 2018 Annual Report from Intercontinental Exchange, the "data and listings segment generated revenues of $2.6 billion in 2018 and accounted for 51% of [the] consolidated revenues."[5] This shows that data and listings can still make profits without any commodities if there are numerous service providers. It is debatable, currently, whether there are currently enough market providers to make an exchange feasible.[22]

Beginning around 2030–2035, SpRCEx would offer storage—at EML-1—and contract/financial rights to purchase or sell deionized water of purity (ISO) 3696 Grade 2. Deionized water will be standardized in grade relative to the purity needed in water-based propellants. Water storage offers a unique opportunity to build a reservoir that supplements supply when sellers cannot meet the demand. In addition, since storage in outer space is neither trivial nor easy to manufacture, it could be considered a commodity itself and provide revenue through renting agreements and storage fees.

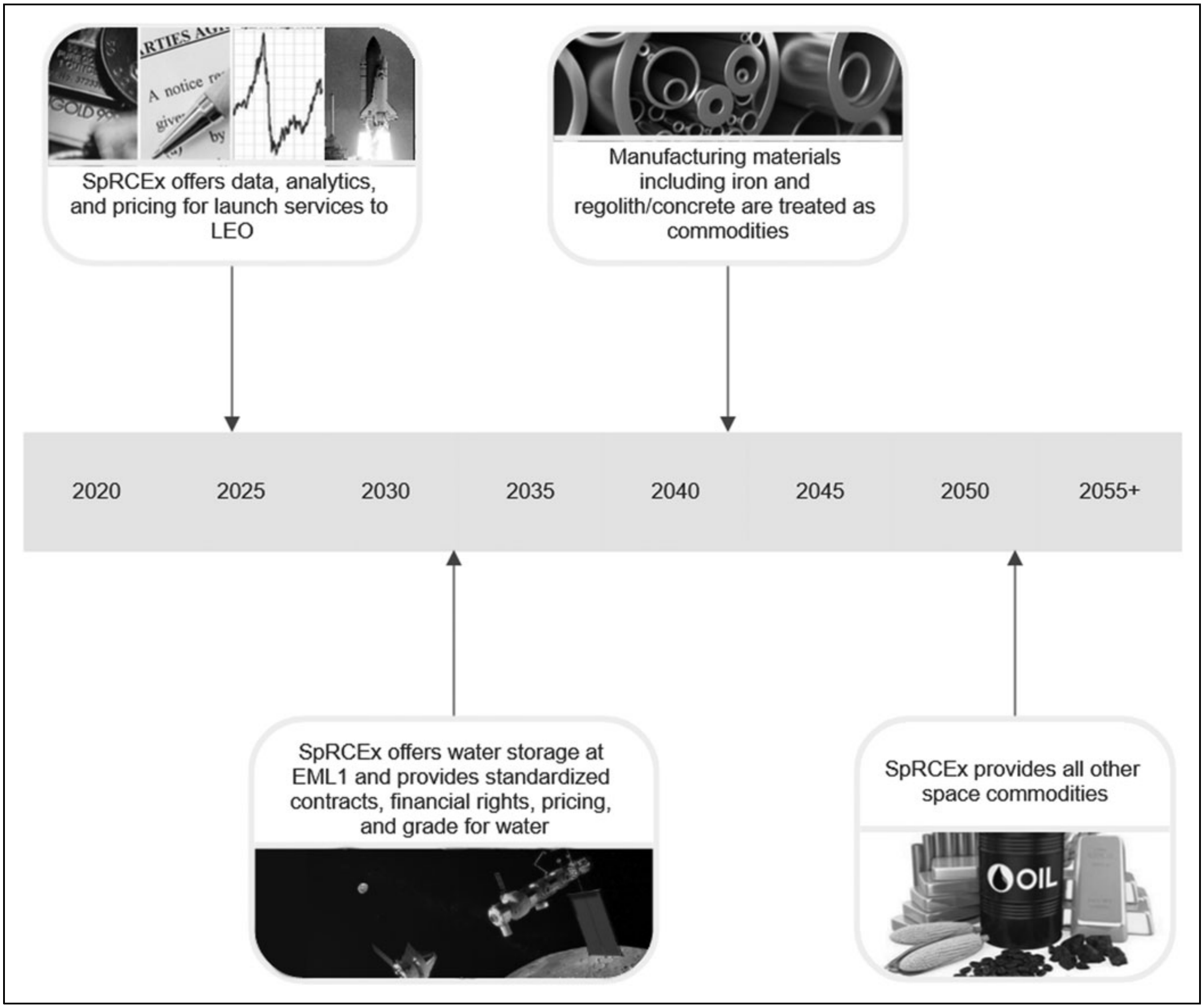

Fig. 2. SpRCEx Establishment Timeline Images: Space Shuttle and Lunar Gateway—NASA.gov. SpRCEx, Space Resources Commodities Exchange.

Between 2040 and 2050, SpRCEx will expand its treatment of resources as commodities to include industry metals and regolith. Both will have high demand for *in situ* manufacturing and construction; however, it is likely that regolith will be treated as a commodity first because it is easier to excavate.

Finally, other resources may be treated as commodities past 2050 but have not been considered in this study because it is generally agreed on that volatiles, regolith, and industry metals will be needed *in situ* before any other resource.

Launch services to LEO. In the past 10 years, an accumulated \$10.4B was invested across 83 different commercial launch providers. As a result, the Federal Aviation Administration (FAA) forecasts an average of 24.3 Non-Geostationary Satellite Orbit (NGSO) launches with 306.1 payloads per year for the next decade.[13] Though commercial launch projections are stable, the proliferation in payloads reflects the industry trend toward launching cargo in clusters, instead of increasing the demand for individual launches. As the quantity of unique payloads per launch rises, so does the significance of launch delay risk to expected cash flow for participants. For customers, the catastrophic and unmitigated downside risk from launch failure deters potential investment in space hardware. For providers, a reputation for delays leads to undersubscribed launches, which are detrimental to business case viability.

By commoditizing the value at risk (VaR) to launch delay, the SpRCEx offers risk mitigation to market participants while generating sufficient revenue to remain viable. Recall a swap is a type of futures agreement whereby one party exchanges their exposure with a floating price for a fixed price, over a specified period. Assume a remote-sensing company is launching a satellite with an average daily VaR of $1K. So, on average, each day of launch delay represents $1K in lost revenue from remote-sensing data. The launch is scheduled to occur in December on a Falcon 9 rocket. To hedge the VaR to launch delay, the company purchases one December SpaceX LEO swap for $15K from the SpRCEx. Each swap contract is standardized to allow 15 days of delay in the contract month at $1K daily VaR, with expiration at month end. In November, assume the FAA bans all commercial rocket launches until January. Since a December launch will not take place, the swap seller is obligated to pay the additional 15-day delay margin to the purchaser. In this case, the remote-sensing company receives a swap profit of $15K, offsetting the aggregate value of sensing data lost in December. Alternatively, if SpaceX launches as scheduled in December, the cash flows vary by launch date. For example, a December 15th launch date represents equilibrium, or a net-zero margin in contract value, since the swap contracts are standardized to include 15 days of delay. A December 1st launch results in a net loss of $15K to the purchaser, since they receive an additional 15 days of data generation.

Offering swap contracts enables purchasers to pay a fixed price now to cap the downside risk of a future launch delay. Providers sell the contracts to ensure full subscription and to demonstrate confidence in their launch capability. In addition, mitigating risk through derivatives reduces reliance on traditional insurance coverage, a major expense for customers and providers alike. By standardizing contract price to VaR, higher-risk customers can simply increase swap purchase value to meet their unique aggregate risk. Further, the SpRCEx can earn revenue by creating a data marketplace with risk profiles for various launch providers, creating an income stream independent of transaction and clearing fees.

Storage. For additional revenue, an exchange could offer deionized water storage at EML-1. Water purity would be standardized by SpRCEx and required to meet ISO 3696 Grade 2.[14] This purification standard is common for PEM Electrolyzer systems, as it helps extend the life of the electrolyzer membrane. Meeting this standard would be required of the suppliers and validated by the exchange.

Storage at EML-1 is a potentially lucrative service. By providing storage, and consequently increasing revenue, a private exchange could supplement this revenue to help establish and grow the exchange as the space economy grows. Three benefits of water storage are listed:

(1) Operations in space are difficult and expensive, which lead to high volatility in on-time delivery and price fluctuations. A reservoir of water at EML-1 would help mitigate this risk for buyers.
(2) Water can be purchased for use in several industries, including electrical power, radiation shielding, rocket propellant, and life support. A large supply at any given time results in meeting higher demand.
(3) Storage in space is not abundant or easy to manufacture and maintain; it is feasible to charge a storage fee to suppliers.

Financial Model

A high-level financial model was created on an annual pretax basis to collate the potential revenues and operating costs for the SpRCEx over a 30-year period. A number of assumptions were made that form the basis of the model:

- This is a single-product exchange that deals with water in space.
- No exchange-maintained storage facilities are considered in the model, and storage is assumed to be available at zero cost to the exchange.
- All prices are delivered/received prices (cost, insurance, and freight [CIF] for delivery, free on board [FOB] for pickup).
- Material inputs and outputs are matched on an annual basis.

The model requires the creation of a price profile and volume profile. To approximate a price profile, a series of calculations were undertaken to generate an annual H2O price. The calculation is seeded with a price of US$5,000/kg. A random number generator was used to generate values between (–1, 1) for each period. The random result was interpreted, as numbers less than zero provide for a price walk in a negative direction and numbers equal to or greater than zero provide for a price walk in a positive direction. The walk direction was then applied sequentially to the price profile in the model. That is, each year's price is dependent on the previous price. The change magnitude on an annual basis was set to 20%. The generated price profile is provided in *Figure 3*.

For exchange volumes, a starting point of 5,000/kg/a was used and an annual growth rate of 1% was assumed.

Exchange membership (participants): Four participants are assumed at the start with an annual growth rate of 7% with no partial participants considered.

Cost and revenue assumptions are outlined in *Table 2*.

The results of the model are outlined in *Figure 4*. It is important to note that, as modeled, the exchange is a loss-making

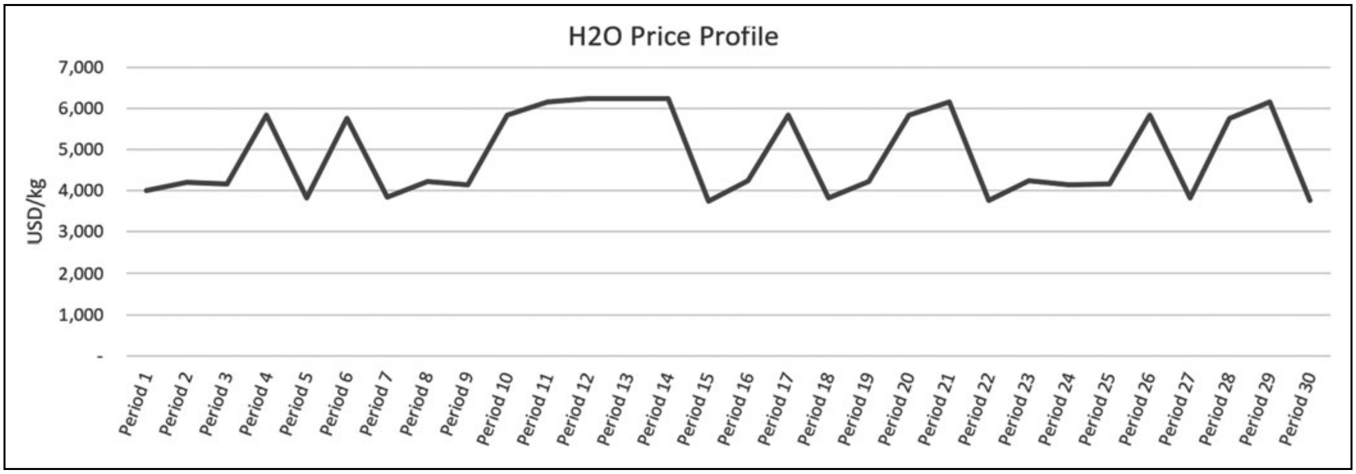

Fig. 3. Modeled price profile.

enterprise to start. As market volumes and as the number of participants increases, the exchange moves toward profitability.

Interestingly, the move to exchange profitability is closely related to the number of market participants. This is primarily driven by the membership fees and the data package sales to market members. The sensitivity to increased material volume is not as strong. Although there is still a positive impact from an increase in exchange fees, the leverage in the exchange as modeled favors increasing market participants as a key driver.

The costs of operating the exchange are essentially fixed, as no physical infrastructure is being maintained and the cost does not scale with an increase in market volumes or participants.

For an SpRCEx to be sustainable, it must make a profit. Space is expensive and difficult to explore, mine, and live in, which makes a commodity exchange even more difficult to establish. The key take-away from this analysis is that market size and volume are key criteria that will ultimately determine whether or not an SpRCEx is profitable.

Table 2. Cost and Revenue Assumptions

Model Inputs	Units	Values
Revenue		
Processed Goods	Percent of Material Value	0.5%
Membership Fees	USD/annum	$12,000
Data Sales Take Rate	Percent of Membership	80.0%
Data Package Price	USD/annum	$24,000
Costs		
Exchange Operating Costs	USD/annum	$100,000
Exchange Infrastructure	USD/annum	$150,000
Data Analytics	USD/annum	$50,000
Legal Costs	USD/annum	$100,000

Pros and Cons of an Exchange

Pros

Price discovery. Commodities markets facilitate price discovery, which for a commodity reflects knowledge about the product on an open market.[15] Market transparency enables accurate pricing, as supply and demand are analyzed in real time. Participating members benefit from access to accurate information about supply and demand of a particular product, permitting better allocations of resources for more efficient business operations. Under direct transaction, companies will not necessarily know at what price potential buyers are willing to buy their product. In an exchange market, anyone can see at what price other participants in the market are willing to buy or sell a product, enabling fair, efficient, and transparent discovery. This transparency in market information allows companies to predict prices based on trends in the market, subsequently lowering volatility of a product. In addition, this shows interest in a market over time.[2,15]

The ULA has set price points for their willingness to buy water at various orbital regions,[12] but this is the only available price information in the Cislunar economy. As more suppliers enter the market, increased supply capacity will reduce price volatility, an important step in the development of an emerging market.[15] Without an exchange in place, accurate market pricing may not be available to all participants. Some companies will actively keep this information private to protect their position in the market. Less-informed entities may not know what is economically feasible in the market. An exchange will improve price discovery, empowering less-informed entities with better market information.[15]

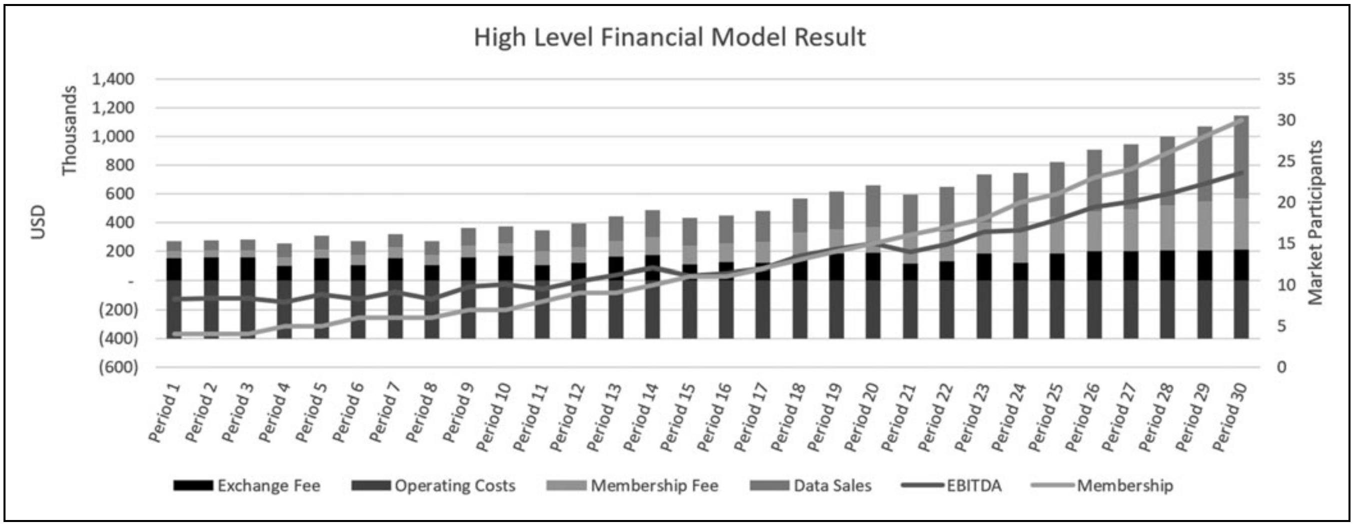

Fig. 4. High-level financial model—result in USD.

Risk management. A derivatives market offers risk management solutions by the use of futures contracts. Volatility in commodity pricing represents a significant financial risk. Uncertainty in future prices makes it difficult to evaluate the economic viability of a commodity. The resulting lack in expected cash flow stability makes buyers and sellers risk-adverse.[15] In addition, without a known price of sale or operations costs, financing and investing in these operations becomes riskier. Futures contracts allow buyers and sellers to develop business models around a guaranteed fixed price in the future. Hedging is a valuable financial tool to mitigate risk, allowing buyers and sellers to focus on a business model that is economically feasible under defined conditions.

In a space resources economy, there will be tremendous engineering risk, financial risk, safety risk, and health risk associated with business models and mission architectures.[12] The ULA case study highlights the shortcomings of direct agreements, and the significant economic repercussions of counterparty delinquencies. An exchange is the seller for every buyer, and the buyer for every seller, eliminating potential counterparty risk. In addition, the exchange will set standards for market participants, reducing the risk for bad operators. Inconsistent supply and demand add more risk to the current space economy, which participants will look to mitigate.

Liquidity. Exchanges offer liquidity through standardization of products and contracts.[2] Commodities are standardized by a grade of material; each commodity will adhere to these standards. Futures contracts specify the quality, quantity, time, and location for the underlying commodity; only the price will fluctuate.[16] This standardization attracts speculators, investors, and hedgers into the market to rapidly buy and sell contracts, increasing the total volume of contracts traded.[15] In a direct transaction market, finding a counterparty to buy or sell an underlying commodity is a time-consuming process. Opposingly, in a liquid market operating through a commodities exchange, transactions occur almost instantaneously.[17] This is facilitated by the purchase or sale of a standard commodity through a uniform transaction process that all parties understand. An exchange raises awareness of quality requirements for industry by setting transparent quality standards. With clear economic benefits to be gained, producers are encouraged to meet quality standards to ensure access to the exchange. In addition, an exchange creates a storage and transportation network surrounding the infrastructure of trade around a certain commodity.[15]

Standardization of space resources helps establish starting points for business models that are reliant on these commodities. CubeSat standardization, as previously discussed, is responsible for the proliferation of the satellite market,[1] providing a uniform starting point for new businesses attempting to meet the needs of new customers. Standardization attracts more market participation, notably speculators whose goal is to profit on counterparty risk.[2] In addition, it facilitates the development of infrastructure and storage needed for the commodity being traded. For example, the SpRCEx may set up storage facilities in various orbital locations, providing a place where organizations will physically trade and store commodities.

Cons

Participation costs. Exchanges charge a fee per contract traded, varying based on the type of contract and status of the participant. In general, transaction fees range from a few cents to a few dollars, with higher fees imposed on more volatile or less understood markets such as Bitcoin.[18] Fees are attributed to both the buyer and seller of a trade. Certain exchange participants pay an annual membership cost to receive discounted fees for trading. Membership processes vary depending on the exchange and range from a few 1,000 dollars to half million dollars per year. The CME Group only allows for 625 members at a time, with a recent membership purchase totaling $410,000 in September 2019.[19] An entity opting to forego a membership will instead utilize a brokerage firm to trade on account of the company, albeit at an additional premium.[6] Beyond fees and membership cost, exchanges charge customers for market data compiled on a subscription basis. As previously mentioned, dataset delivery is a significant revenue stream for major exchanges such as CME and ICE.[20]

Participants in the commercial space economy need to factor in fees, memberships, and data services to their projected operating expenses. Related to the market for water, without vibrant participation for an extended period, a valuable data sharing service is not a viable near-term offering from the SpRCEx. Market participants seeking to purchase data services will find little value until participation increases, particularly for the supply of water in space.

Facilitator costs. An exchange requires significant capital to set standards for commodities and contracts. Resources are needed to confirm product grade, operate the exchange, offer storage, and deliver the product.[15] Exchanges form under various ownership structure, whether government operated, donor funded, or private entity. Each type of exchange would follow different strategies of raising start-up capital for operation. In emerging markets, most donor-funded or government-led exchanges cease to exist once donor support stops.[7] Therefore, the exchanges that operate with the most volume are private, for-profit entities.[21] A private exchange model is most sustainable, as the exchange itself is incentivized to produce valuable products for its customers.

For the SpRCEx, confirming the grade of commodities produced off-world will require considerable capital investment, especially in the case of water. For example, water with a grade of ISO 3696/2 Grade 2 is already determined as propellant electrolyzer ready-grade water. Grades will need to be determined for each utilization of water, including life support systems. Regulation of product quality in space represents a significant cost differential compared with terrestrial operation. Additional investment is needed to create infrastructure, storage, and other facilities to permit the full spectrum of services offered by the SpRCEx. Reliable revenue streams will need to be developed to generate ample cash flows for operation and market growth.

Contract specifications and limitations. Futures contracts have a set quality, quantity, time, and location of the commodity for each specific contract. For example, some of the highest traded energy futures contracts are crude oil. The CME group's most successful energy contract is WTI Light Sweet Crude Oil Futures, with a total volume traded of 306,613,007 in 2018.[10] This contract is standardized to 1,000 barrels per contract.[11] Given the price volatility of crude oil, a large number of participants see value in trading this specific contract. However, if the price for WTI Light Sweet Crude contracts is too high, or if the grade is less than optimal, this contract may not be suitable for specific customers. If the contract does not meet customer expectations, it will not be traded and the exchange will miss out on potential revenue. A significant fraction of contracts die within the first 5 years of creation. However, if a contract lasts past 6 years, it has a higher percentage of lasting more than 20 years.[17]

Contract specifications are an important factor to either limit or promote trading volume on an exchange. If participants find an issue with certain specifications, all interested parties will be worse off. The SpRCEx needs to ensure contracts are tailored to the demands of prospective market participants, to promote liquidity and standardization.

CONCLUSION

Recent evidence of water on the Moon and Near-Earth Asteroids offers opportunities for a future SpRCEx. Given the assumptions mentioned at the beginning of this article and utilizing the bootstrapping models suggested, water could be treated as a commodity and the SpRCEx could incentivize growth and increased participation in the space economy.

Due to the importance of water for use as a rocket propellant in space, water is likely to be the first resource that should be treated as a commodity and has the potential to be hosted on an exchange. A commodities exchange will have the benefit of allowing market participants a tool with which to effectively manage commodity price and availability risk in space. When risk can be effectively managed, the business cases for development of space and space resources become more robust as key risks are mitigated. This has the potential to accelerate the development of the sector, as companies participating in an exchange find new lower cost pools of capital that are only accessible in lower risk environments. This impact is visible in the case study outlined earlier, as it highlights the operational risk that businesses face in the unique environment that is Cislunar space. The case study drew an analogy to price and availability of jet fuel in existing markets and extended it to the environment that transportation companies in space will operate in. Although water is the obvious first commodity fit for an exchange, it is likely to rapidly expand into other commodities as volume in those commodities expands and the number of market participants increases.

A space resources-based commodity exchange will operate similarly to existing terrestrial exchanges, where owners of the commodity exchange are rewarded for taking the financial risk associated with running an exchange by collecting transaction and membership fees and recognizing revenue from data and intelligence sales.

Beyond the obvious benefits provided to market participants (managing risk) and owners (financial gain), the exchange also provides some broader benefits that will benefit the community. This is in the form of providing a regulated and controlled market within which market participants can conduct business and have some assurance regarding the integrity of transactions and participating entities.

The work done to date indicates that there is a threshold for material volume and number of market participants at which an exchange becomes economically viable. It is currently unclear exactly what that threshold is. Some other potential revenue streams have been identified, which may help to "bootstrap" the exchange. The development of an SpRCEx will enable and accelerate the development of a space economy and further work is recommend for defining the point and structure at which an exchange becomes viable.

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