How to Pay for Settling Space

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Abstract

Human space-faring societies have been the subject of science fiction and the imagination of countless people desiring a different way of life. Various concepts of what life would be like in space, whether on a spacecraft, space station, or other planets or moons, vary with the imagination of those seeking various idealistic or altruistic reasons. Lifestyles, environmental, and survival technologies have been the subject of engineers, scientists, and human behavior specialists for decades. Payload and volume constraints have limited the practical capability of humans in a space-faring society. Advances in private/public space launch by SpaceX and Blue Origin have advanced space flight with affordability as the key driver. SpaceX is pushing heavy-lift reusable rockets to impressive rocket payloads in mass and available volume. Although cost has been reduced over previous rocket-based solutions, the total cost of creating a space settlement is in the trillions of dollars. How will Earth-based human space settlers pay for the opportunity to settle in space? This paper will explore an integrated space economy concept that will provide how thousands of humans can compensate for Earth-based investment in developing a human space settlement society. Trillions of dollars will be required, but trillions are available to return to Earth-based investors or repay government entities.

Introduction

Independent scientists, engineers, artists, dreamers, and businesses have developed concepts of systems, components, and technologies to meet the challenges of building, deploying, and operating space settlements. Various natural scientists, agriculturalists, and human behavioralists have studied and pontificated what, why, how, who, when, and where a space settlement would be built, occupied, and thrive. Most studies limit the number of temporary space inhabitants to less than one hundred people. However, past futurists, science fiction, and more current space enthusiasts such as Elon Musk and Jeff Bezos suggest settlements of tens to hundreds of thousands, potentially millions of people (Grind, 2024). Alternative rocket technologies became available in the late 2000s to drastically reduce costs compared to their predecessors, Figure 1 (CSIS Aerospace Security Project, 2022). SpaceX is driving the cost of transportation to one-third that of previous rocket-based solutions.

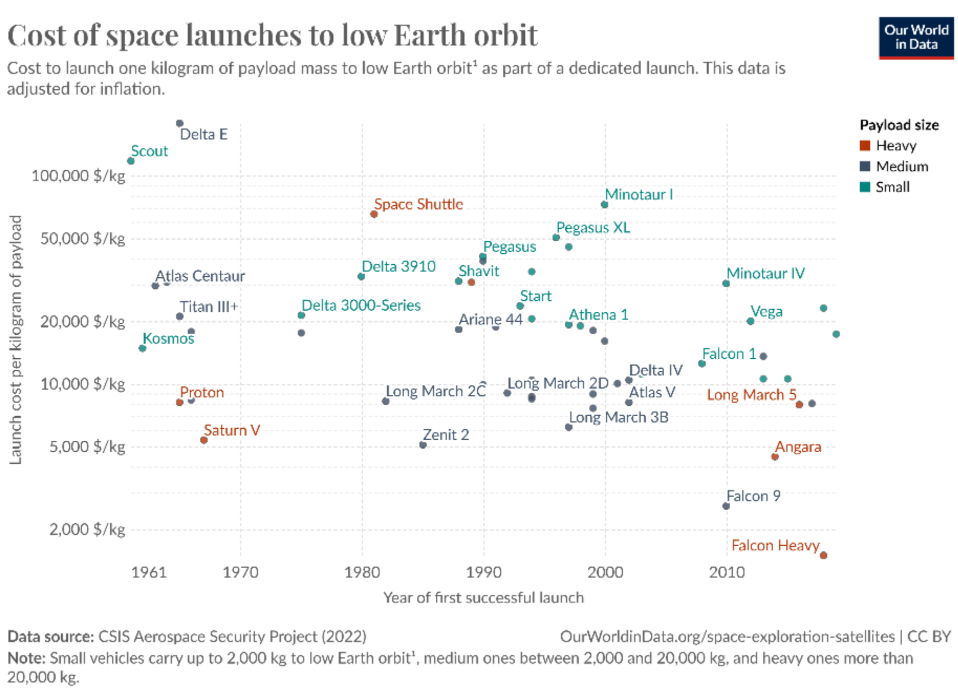

Figure 1 Launch Cost per kilogram has decreased with new rocket designs.

Even with the cost reduction, Griggs (Griggs, 2024a) calculated that the transportation cost of the SpaceX Mars colony, which would require one billion kilograms of mass to Mars, would be over $4 trillion. Assuming the number of settlers would be between 10,000 and 100,000 people, the transportation cost alone would be $42-400 million per person, including housing, clothing, food, and resources to create a permanent settlement. However, the cost of these other resources to create a permanent settlement must be added to the cost per person beyond transportation.

Griggs (Griggs, 2024b) suggests that settlers will eventually have to be self-sufficient. This requires people in the construction trades, manufacturing, health care, food production, and various other services. The previously mentioned costs are unpayable except for the very wealthy. So, how will future labor considered middle and lower economic class on Earth afford to be part of the settlement? History provides examples from slavery to indentured servitude as methods for payment beyond a person's capability. These are not viable options for space settlement. Although a modern version may be agreed upon before becoming part of a settlement, adverse behaviors could lead to a breach of contract. Another method or system must be developed to ensure a settlement has the right skill mix to be self-sustaining, prosper, and have the capability to grow. In addition, future trade between settlements and Earth will require a form of payment for goods a settlement must have to survive, grow, and prosper. The settlement must have a desirable form of wealth creation that is of value to Earth or other settlements.

The initial cost of starting a space settlement is vast since everything must be sent to a space settlement from Earth. The transportation costs are the driving factor, and as the settlement becomes more self-sufficient, the cost associated with Earth-provided resources will lessen. A billion kilograms for the settlement mission's initial phases will cost trillions of dollars. More mature self-sufficient settlement cost reimbursement to Earth-based companies and governments are expected to drop to billions of dollars. There is uncertainty about what a future space economy will develop into and the nature of the interactions between a settlement and Earth or between different settlements. Paying for settling space will depend on the cost associated with each settlement phase. The transition from a startup to a mature settlement and the repayment method available to the settlement.

Space Settlement Phases to Self-Sufficiency

Space settlements must become as self-sufficient as possible due to (1) the time required to transport needed products from Earth or (2) Musk's concern that an Earth annihilating event occurs, requiring a large enough population to ensure genetic viability for the species. As a settlement progresses from a startup to a mature state, it is expected to transition through a typical life cycle. It will follow the process of:

- startup,
- emerging,
- developing,
- growth, and
- maturation.

The early phases of the settlement will be highly dependent upon Earth for almost all their needs. Transportation is expected to be the primary cost driver, and a space settlement will have little to offer in terms of payment for the bill. As the settlement becomes more self-sufficient, the payment due to Earth-based companies or governments is expected to lessen. The early phases of development will be in the trillions of dollars, with later phases lessening to billions of dollars. The settlement's startup, emergence, and developing phases will focus on survival and creating self-sustaining living conditions. Survival will take precedence over wealth creation. Repayment by the settlement with settlement efforts and labor will shift to later phases of the settlement's life cycle. This will lead to increased accrued interest that will be added to the overall cost once the settlement begins a repayment effort.

A notional top-level resource, transportation, and cost assessment for a billion-kilogram space settlement of 10,000 to 100,000 people is provided in Figure 2. This is not an all-inclusive list but includes the significant needs for survival and growth. Entertainment, luxury goods, favorite foods, personal care items, and other non-survival-related products will be imported in the earlier phases, and once the settlement is in the growth or maturation phase, various cottage industries, crafts, and artisans can be expected to contribute to the local economy and reducing the amount of imports. Eventually, production equipment will be imported, and various goods will be

Settlement Phase	Resource Needs	Transportation	Capital Needs
Startup	• Immediate: food, clothing, water, air, shelter • Food Production: water, soil, carbon, nitrogen, tools • Construction equipment • All technology • Medical equipment and medication	• Everything shipped from Earth	• Trillions in equipment and supplies • Trillions in transportation cost
Emerging	• Periodic: clothing, shelter • Food Production: periodic carbon, nitrogen, tools • Construction equipment • All technology • Medical equipment and medication	• Mostly shipped from Earth • Metals from asteroid mining • Potential carbon & nitrogen asteroid mining	• Trillions in equipment and supplies • Trillions in transportation cost • Local capital markets established
Developing	• Periodic: clothing • Food Production: periodic carbon, nitrogen, tools • Construction equipment • All technology & production equipment • Medical equipment and medication	• Mostly shipped from Earth • Larger share of metals from asteroid mining • Potential carbon & nitrogen asteroid mining • Beginning to produce goods locally	• Billions in equipment and supplies • Billions in transportation cost • Local capital market expanding
Growth	• Periodic: clothing • Food Production: periodic carbon, nitrogen, tools • Construction equipment • Most technology & production equipment • Medical equipment & medication	• Mostly shipped from Earth • Larger share of metals from asteroid mining & local • Potential carbon & nitrogen asteroid mining • Producing more goods locally	• Billions in equipment and supplies • Billions in transportation cost • Local capital markets providing growth
Maturation	• Periodic: clothing • Food Production: periodic carbon, nitrogen, tools • Construction equipment • Non-producible technology • Medical equipment and medication	• Partially shipped from Earth • Most metals from asteroid mining & local • Potential carbon & nitrogen asteroid mining • Producing most goods local	• Billions in equipment and supplies • Billions in transportation cost • Local capital markets maturing & self sufficient

Figure 2 Space Settlement Resource Needs from Earth Incurs Method of Payment Issues for Settlements Which Lessen as the Settlement Matures.

manufactured locally. Capital markets will develop, providing financing to entrepreneurs and experienced product manufacturers.

The cost of creating a self-sufficient, permanent, and thriving settlement will be in the trillions of dollars. A space settlement on the moon, Mars, a space station in and of itself, cannot produce trillions in wealth to repay the cost of the settlement, especially if the time value of money is considered for repaying an investment from capital markets. An alternative approach must be used to ensure the capital will be made available on such a large scale and that there is a timely method by which trillions of dollars of invested capital can be repaid with an adequate risk-adjusted return. This mandates space-based wealth creation of rare or impossible products on Earth and/or services that can be created or supplied from space.

Value creation from the Earth-based capital markets will be based on three focus areas: (1) rare or impossible to create on Earth products that can be brought back to Earth from space with a respectable profit, (2) Earth orbiting structures that Earth values for its reasons, and space resources that are rare on Earth or Earth would have to provide for their space manufacturing or settlement interest, Figure 3. Zero-g manufacturing will add value but can easily be managed by Earth-based companies and would not necessarily require a settlement interaction. Orbital Earth projects are similar in that Earth-based companies can manage them. There can be interest in great masses of construction material that space settlements could provide versus lifting the material from Earth.

This leaves space-based rare Earth metals and construction materials as the most probable solution to wealth creation for repaying Earth-based investors. Rare Earth metals have high value and should be compact enough to reasonably transport them to Earth from space locations beyond Earth's influence. The current market value of space-based rare Earth metals is in the trillions of dollars and is more than adequate to repay an investor. However, a different model is required to develop a space-based economy.

An Integrated Space Economy Model Approach

Earth-based economies are highly integrated. A space-based economy may be required to be even more so than an Earth-based one. An Adam Smith-type economy (Smith, 1991), where people who look out for their self-interest benefit society, maybe more in line with a developed economy. Newly formed space economies and settlements ("startups") have monumental formation costs, and the only source of capital to finance and invest in a new settlement and economy is Earth-based investors and organizations. Estimates can be made for the cost or investment in space settlement, manufacturing operation, or mining operation in various space environments. The costs define the investment quantity. The legitimacy of the actual cost projections will be in question until more detailed designs are made on actual

	Zero-g Manufacturing	Orbital Earth	Space Resources
Earth-Focused Value	• Crystal growth ○ Semi-conductors ○ Other electronic devices ○ Specialty windows and optics • Medicine manufacturing ○ Protein crystals • Advanced fiber optics • Human organ growth	• Mega structures • Solar power beamed to Earth • Sunshade to minimize global warming • Large-scale orbital manufacturing targeting Earth-based consumption	• Rare Earth metals • Construction materials for orbital Earth projects • Water, fuel, carbon, nitrogen for space applications
Potential Value	• Billions	• Billions to Trillions in cost avoidance	• Trillions in rare Earth metals

Figure 3 Space Settlement Sources of Value to Repay Earth-Based Investment.

facilities and transport vehicles for long-term or permanent settlement or operations. The investment return will depend on how payment is and by what payment schedule the investor can expect compensation. After this, a risk assessment can be conducted to determine the minimal rate of return and incentivize the investor. The crucial point is what is of value in space that can be returned to investors on Earth.

Various space enthusiasts have suggested that harvesting metals valuable to Earth from various space bodies can provide building materials for space habitats or facilities or be sent to Earth(Dietzler, 2020; Lewis, 1996; Sivolella, 2019). High-value commodities are the best return payment play for investors.

Mining the Moon, Mars, or other rocky asteroids can provide valuable metals. The quantity of ore required to be processed may need to be improved to provide a return to the investors on the trillions of dollars required to set up a space settlement. There are specific classes of asteroids, the “m-class,” almost entirely composed of metals when formed. Concentrations of valuable and rare-Earth metals in the precious and platinum group metals can be significantly higher than those found on Earth. Several are not pursued due to their concentration levels, and the quantity of ore required to process is uneconomical.

Lewis (Lewis, 1996) refers to Asteroid 3554 Amun as a thirty billion kilogram mostly metallic asteroid worth over $20 trillion—Asteroid 3554 Amun will be explored in more detail. He stated that at that time, iron and nickel content was worth $8 trillion, cobalt was worth $6 trillion, and platinum was worth $6 trillion. It was not disclosed how these values were estimated, but the notion that a Near-Earth Orbit (NEO) asteroid would have over $12 trillion in rare earth could more than pay the cost of space settlement on Mars.

An Integrated Space Economy Model (ISEM) refers to the concept of an asteroid mining operation paying for other space settlements. A highly profitable geographically separated operation finances a high-cost settlement, habitat, or other operation that cannot be justified economically as a separate entity.

The relationship between an asteroid mining operation and a settlement seems viable as settlements are founded and grown. An asteroid that has vastly superior profitability beyond the cost of a settlement provides various economic possibilities as to how much of the asteroid’s wealth is sent to Earth to pay for the investment and the amount that can be left in space to provide materials for growing the settlement and creating new products and services. Before a hypothetical future space economy is discussed, the value of an asteroid mining operation over a reasonable timeline must be assessed. In addition, the potential return on investment and logistics of valued metals returning to Earth must be assessed. The total value of all the minerals in this solar system is far beyond that required to compensate settlement investors. Near-Earth Asteroids make the most sense to assess due to their proximity to Earth and the desire to bring a significant fraction of the precious metals or Platinum group back to Earth.

What is the Extractable Value of an Asteroid Mining Operation

Asteroid 3554 Amun has been a focus of asteroid mining discussions of Near-Earth Asteroid mining concepts (Lewis, 1996). Lewis stated that the value is approximately $20 trillion. How that valuation was determined was not provided in his claim of the value in 1996 dollars. An independent assessment of what the asteroid may be worth is in order.

Asteroid and comet mass composition and concentration levels have been the subject of various scientific papers using various imaging techniques. Radars and various wavelengths of light have been used to determine with some accuracy what a typical metallic asteroid or comet may consist of. These are compared with asteroid fragments found on Earth.

Although various sources disagree on composition and concentration, a data set was selected and used conservatively to define the wealth of an asteroid (Blair, 2000; Cannon et al., 2023). Blair identified three different concentration levels for metallic asteroids based on sources at that time, Figure 4. Distant imaging techniques and methods for determining the composition and concentrations of these metals will have a measure of uncertainty. Only large-scale contact-based inspection of metallic asteroids is conducted, and there must be assumptions to calculate amounts and value to pursue an asteroid mining operation.

An assessment of the return on investment for a Mars space settlement will be based on a Near-Earth Asteroid 3554 Amun mining operation. This asteroid is the smallest known "m-class" in a near-Earth orbit, with an average diameter of approximately 3.3 kilometers. It provides an excellent first proxy for extracting wealth from asteroid mining. Assuming the total mass of the asteroid is thirty billion kilograms and focusing on the most conservative composition from Blair for a 90% iron composition and subsequent precious metal (PM) and platinum group metals (PGM), the value of the PM and PGM can be calculated, Figure 5. This composition also assumes that waste is approximately three billion kilograms of rock or other non-valued material. Then again, alternative construction concepts may use that material for shielding or other uses.

Assuming that the PM and PGM are evenly distributed throughout the asteroid, an assessment of PM and PGM metals availability for returning to Earth can be made. Using conservative concentrations, approximately 4.7 million metric tons of PM and PGM are available, with a current market value of approximately $70 trillion. This does not include the $2.4 trillion market value of iron. The low value and high mass of iron do not make economic sense to return to Earth as payment for investors. However, it has value in space since launch costs from Earth are not required. Space transportation costs from the mining site to the needed sites still must be considered. Mining a carbon-based asteroid and using iron and carbon to make billions of metric tons of steel has space applications that have yet to be considered in the past due to the lift cost of steel from Earth.

Considering the wealth brought back by asteroid mining, two factors drive the investment return. One is the expected metal quantities that can be transported to Earth regularly. The second is the time required to process the asteroid. Assuming that the PM and PGM concentrations are evenly distributed, a weighted average portfolio of these

Asteroid Composition: Parts per Million (PPM)			
Iron	Avg LL Chon	90% Fe	98% Fe
Precious Metals (PM)			
Germanium (Ge)	1020	70	35
Gold (Au)	4.4	0.7	0.6
Platinum Group Metals (PGM)			
Rhenium (Re)	1.1	1.1	2.4
Ruthenium (Ru)	22.2	20.7	45.9
Rhodium (Rh)	4.2	3.9	8.6
Palladium (Pd)	17.5	2.6	1.2
Osmium (Os)	15.2	14.1	31.3
Iridium (Ir)	15	14	31
Platinum (Pt)	30.9	28.8	36.8
Total	1130.5	155.9	192.8

Figure 4 Precious Metals and Platinum Group Metals Concentrations on "m-class" Asteroids are Greater Than on Earth.

Asteroid Comp	Metal Concent (PPM)	Total Mass (Mkg)	$/kg	Total Wealth (trillions)	% World Annual Production	Portfolio Weighted Average
Iron	90% Fe	27,000,000	$ 0.092	$ 2.484	1176%	
Precious Metals						
Germanium (Ge)	70	2,100	$ 3,883	$ 8.154	750000%	$ 1,743.49
Gold (Au)	0.7	21	$ 84,300	$ 1.770	500%	$ 378.51
Platinum Group						
Rhenium (Re)	1.1	33	$ 2,489	$ 0.082	133333%	$ 17.56
Ruthenium (Ru)	20.7	621	$ 12,538	$ 7.786	4590000%	$ 1,664.76
Rhodium (Rh)	3.9	117	$ 155,931	$ 18.244	860000%	$ 3,900.78
Palladium (Pd)	2.6	78	$ 34,561	$ 2.696	17143%	$ 576.39
Osmium (Os)	14.1	423	$ 1,653	$ 0.699	187800000%	$ 149.50
Iridium (Ir)	14	420	$ 4,650	$ 1.953	11625000%	$ 417.58
Platinum (Pt)	28.8	864	$ 32,000	$ 27.648	184925%	$ 5,911.48
Total	155.9	27,004,677		$ 71.517		$14,760.05
Total Less Iron		4,677		$69.033		

Figure 5 PM and PGM Concentrations on "m-class" Asteroids Provide Tremendous Wealth Capture Opportunities.

metals was constructed based on their concentrations. Figure 5 provides a weighted average PM and PGM portfolio value based on their concentrations and current market value. The calculated value is one kilogram of the metals based on their comparative concentration to the total PM and PGM mix. This provides a net value of $14,760 per kilogram of portfolio metals sent to Earth.

The time required to process the asteroid will be based on the effort and equipment sent to accomplish the task. It is noted that metallic asteroids are unlike metal-bearing ores on Earth. The concentration of the metals is remarkably high, and the processing requirements for removing unwanted soil are considerably lower. The asteroid is mainly comprised of iron and based on worldwide production; it is estimated that it would take at least ten years to process the asteroid. Startup and operations growth suggest a more conservative twenty-year target is the most optimistic. A less enthusiastic mining operation could take considerably more time.

A twenty-year processing window provides a daily estimate of PM and PGM that can be transported to Earth at 640.7 metric tons valued at approximately $9.45 billion per day based on current market value. Assuming daily deliveries and various possible capital costs, the time horizon for investors to recuperate their investment is well within the asteroid mining operation timeline, Figure 6. This assumes that shipments are received on the first day of operations, which is impossible.

They are considering sending equipment to Mars and the Asteroid at the same time. Asteroid mining operations begin and scale to the point where the first shipments of PM and PGM arrive on Earth five years after operations commence. Assuming the capital for mining equipment and space settlement can have alternative uses, a lower risk rate of return is assumed. Assuming a debt obligation of 8% for the operational period leading up to the first refined metals returning to Earth, the payback period is increased, as depicted in Figure 7. A higher return due to risk was assessed once PM and PGM metals started returning due to the following:

- uncertainty of the composition and concentrations of PM and PGM at various locations of the initial mining operation and over the payback period,
- speed of scaling the mining operation on location,

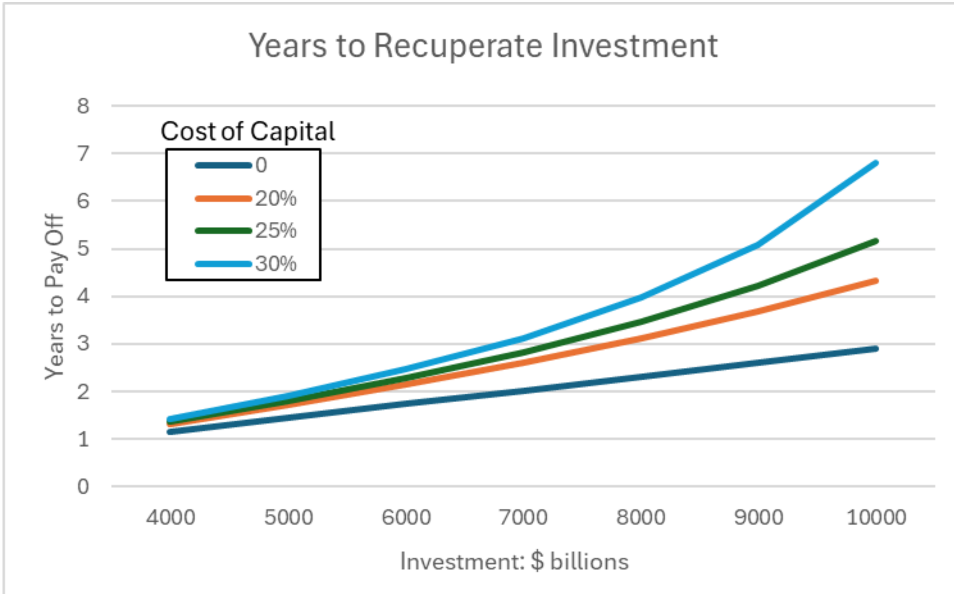

Figure 6 The Investment Recovery Period is Well within the Mining Operation Timeframe.

- reliability and maintainability of mining equipment,
- delivery issues with timely recovery and possible loss of shipment,
- alternative uses of space metals superseding returning PM and PGM to Earth, and
- The risk of price movement in the commodities markets with high influxes of hundreds of percent beyond current worldwide production.

The current market value of the PM and PGM can more than compensate for an Earth-based capital market for investing in space settlement and mining operations.

Realizable Value of Extensive Commodities of an Asteroid Mining Operation

The extracted value assumes that introducing high percentages of metal into the commodities

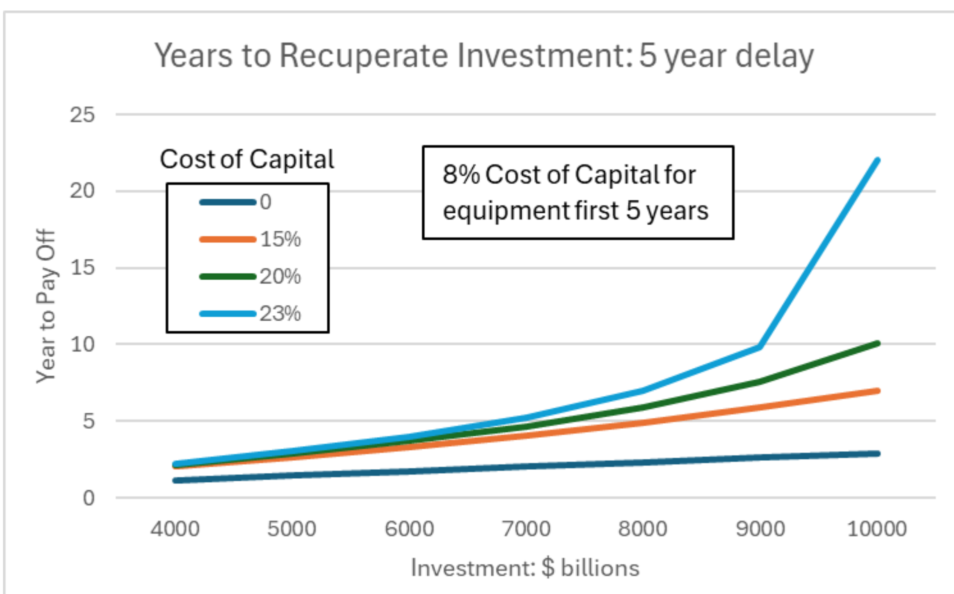

Figure 7 Investment Recovery Period and Return are Reasonable, Including a 5-year delay for setting up operations.

market will not significantly affect the price of that commodity. That may be a reasonable assumption if this was just a couple of percent. However, as shown in Figure 5, the asteroid could flood PM and PGM markets at over 1000% of current world production rates. The price elasticity of demand and supply for PM and PGM is unknown when the supply can be over 1000% more than current world annual production. The impact of previously rare and readily available metals can open new uses due to availability or new uses due to a drastic price reduction. The magnitude of the impact of PM and PGM returning to Earth is highly uncertain and is believed to have nonlinear impacts on the supply and demand for these metals. Alternatively, the amount returned to Earth can be limited to reduce price volatility, but this would take longer to recuperate investments.

Retaining PM and PGM for space applications can also be an alternative and may place more value on the metals versus returning to Earth. A space economy based on trade and the perceived value of commodities, equipment, consumer goods, food, water, air, carbon, nitrogen, metals, and other materials will be speculative at best. With a market proceeding through initiation, emergence, development, and maturation phases, the value assigned to various needs is still being determined. The value may also be settlement location dependent based on the phases a settlement proceeds through as it becomes more self-reliant.

Metals in space do not require the energy and effort required to launch from Earth to arrive at their destination. It may be wiser and more cost-effective to leave them in space and transport them to settlements that can use them. An active market will eventually define the value of metals in space based on a space economy proceeding through its phases.

Value extraction for the mining operation will be a mix of a percentage returning to Earth and a percentage retained in space. In an open market system, the mix will be based on the value maximization of the mining operation and its owners.

As the space economy emerges, various economic considerations will be trial and error, with the market eventually determining the equilibrium. Earlier, it was suggested that space settlements establish mining operations to pay settlement startup costs and future settlement needs.

Space Economy Initially Bound to Earth Economy

Space settlement requires Earth-based investment. Trillions of dollars are required for transportation, let alone the equipment and resources that Earth-based companies and governments will provide. Companies and governments need to be able to afford the magnitude of capital required to enable human settlements in the tens of thousands to millions of permanent occupants. Earth capital markets, totaling $256 trillion, could provide the trillions of dollars required to settle space and create an asteroid mining operation on a grand scale, Figure 8(Kolchin et al., 2024). However, the Earth's capital markets will require a return for the capital they provide. A risk-adjusted rate of return must be agreed upon, and the investment payback period will be greater than typical venture capital time horizons. Even if the combined financing package is as high as $10 trillion, that only accounts for less than 4% of the total overall global capital markets.

It was shown that space settlement can repay debt or equity capital with a reasonable risk-adjusted rate of return within several decades. This will depend on the capital markets' desired return rate based on their perceived risk. There could be a counterpoint that space settlement, once funded, will not honor the contract and repay the capital markets. This has a low probability since many products will still be imported from Earth. Settlements may become self-sufficient from a survival mode but not be able to prosper without the latest technological advances from Earth. Other products that require tremendous capital, labor, or Earth-bound resources will also be imported. True space settlement self-sufficiency will take over a

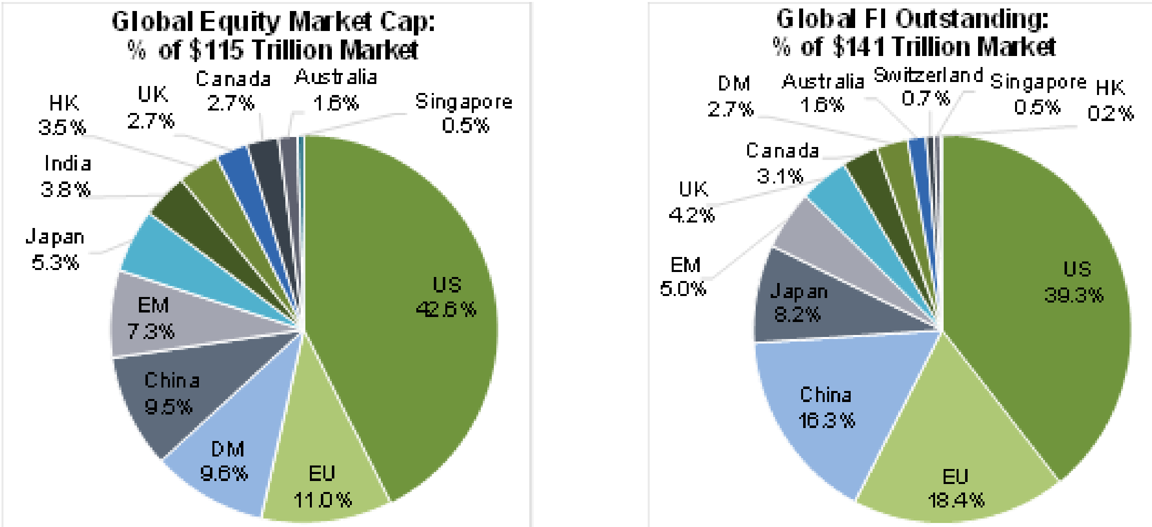

Figure 8 Global Equity Markets and Global Fixed Income Markets Have $256 Trillion in Capital, A Small Fraction of Which Would Be Adequate to Finance a Settlement/Mining Operation (2024 Capital Markets Fact Book, SIFMA: DM = developed markets, EM = emerging markets).

century, but trade will always be in their interest. This trade dependency of the space settlements will ensure that repayments will be made, or dire consequences can be levied on the settlements by Earth trade agreements.

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The key is demonstrating that the business model will work for startup settlements linked to asteroid mining. They do not have to be collocated but should be linked contractually or through common ownership, whether that ownership is company-based or community-based. The first settlement/asteroid mining operation start-up sequence and payback procedure will be governed by the Earth-based capital markets; otherwise, capital will not be provided.

Earth-based commodity markets must absorb the PM and PGM for the model to work. The drastic increase in annual production of PM and PGM may be influenced by space supply, mining operations, and transportation costs to bring those metals back to Earth.

Commodity prices will initially drop with an overreaction shock that will stabilize with a new regular supply and demand equilibrium. When prices drop sufficiently, the PM and PGM will find new applications that were unimagined before due to cost. Once the investment is paid in whole, other expenditures in space requiring Earth-based resources may continue to be financed by space mining operations. However, the PM and PGM quantity may be reduced, and retaining those metals for space settlement may take precedence. This will depend on the rate at which new settlements are established and how they may be linked to asteroid mining operations.

Emerging Space Economy More Independent

As space asteroid mining repays Earth-based capital markets for the initial investment, a more independent space economy will develop and be less heavily bound to Earth-based systems. Specialized resources from Earth will be required, and systems will be developed, such as international trade on Earth (Krugman & Obstfeld, 2000). The most significant differential is transportation costs.

Transportation cost influences few current international trade theory applications. Productivity, land, capital, and labor form the basis of most international trade theory concepts; for emerging space settlements developing their economy based on growth and survival resource needs, most food, water, air, and basic build materials can be obtained at the local settlement geographic location. More advanced technology that requires large scale, such as computer chips, heavy equipment, medication, space suits, or other hard-to-synthesize products, will require trade from Earth. Again, asteroid mining is a tradable product for the complex to produce space settlement products, Figure 9.

Reducing the amount of PM and PGM sent to Earth will also increase its value, and less will be required to obtain the desired products from Earth. The exception would be products only made in low-g or zero-g environments. These will probably be made on Earth-orbiting space settlement manufacturing complexes. However, if asteroid mining produces raw material more efficiently than supplying it from Earth, then other asteroid types with high carbon, nitrogen, or water may provide new trade goods for Earth.

Expanding the Space Economy will Develop Its System.

Earth-based systems with various economic theories and legal concepts are a good starting point for a developing space economy. Land, labor, capital, and productivity form the basis of various Earth-based theories. Distance between space settlements and trading partners, as well as the cost of transportation, must take a more prominent role in the theory to understand how the space economy may develop and mature.

The concept of a basis of value (price) and what the transaction medium will be (currency) is of interest. Will it be based on:

- an Earth-based currency,
- various settlements having their currency (cryptocurrency),
- PM or PGM,
- oxygen or water,
- various other commodities or

Settlement Phase	Capital Needs	Payback Potential
Startup	• Trillions in equipment and supplies • Trillions in transportation cost	• Settlement sponsored asteroid mining operation
Emerging	• Trillions in equipment and supplies • Trillions in transportation cost	• Settlement sponsored asteroid mining operation
Developing	• Billions in equipment and supplies • Billions in transportation cost	• Settlement sponsored asteroid mining operation
Growth	• Billions in equipment and supplies • Billions in transportation cost	• Settlement sponsored asteroid mining operation • Settlement created trade goods
Maturation	• Billions in equipment and supplies • Billions in transportation cost	• Settlement sponsored asteroid mining operation • Settlement created trade goods

Figure 9 Space Settlement Repayment of Earth-Based Capital Markets Requires Settlement Sponsored Asteroid Mining Operations Which Lessen as the Settlement Matures.

- a transportation metric (delta-V, energy to transport, time in transit, etc.)

A transaction medium must be created that considers differences in the value of various goods and supplies depending on the settlements' needs or wants. These differences suggest that multiple currencies must adapt international financial theory to space economic needs (Caves et al., 1999).

A space economy will also require property rights laws and court systems to enforce the law. This can be the most challenging. Current Earth-based legal systems are attempting to put laws into place that will hamper property ownership and harm development. It may be a good starting point, but each settlement will develop its property rights and ownership system. The settlement's prosperity will require this important legal system as DeSoto (De Soto, 2000) described the success of the West's economic systems as dependent on property rights and courts to enforce them. We should expect a thriving economy in space to be built on a similar system.

Paying for Space Settlements and Uncertainty

Space Settlement startup costs, development, and growth have an avenue for repaying significant investments from Earth-based capital markets. The wealth of space can repay investments with various commodities. However, the magnitude of the PM and PGM's ability to repay the investment and agree to return is subject to various uncertainties. These include:

- actual PM and PGM concentrations in the targeted asteroid,
- asteroid mining scalability to extract PM and PGM and refine ready to ship to Earth,
- transportation system to Earth or other destinations,
- transportation from Earth's orbit to Earth's surface
- mass of PM and PGM returning to Earth each year
- reaction of commodity markets to an influx of PM and PGM
- alternative uses of PM and PGM on Earth or in space

Each of these uncertainties can add cost to returning wealth from space to the Earth or impact the amount of wealth returned each year. These can affect investment returns and limit future investment by Earth-based capital markets to space-based settlement, manufacturing, or mining operations.

The current technical challenge for repaying Earth-based capital markets is transportation from Earth's orbit to Earth's surface. 640.7 metric tons of PM and PGM must be transported to Earth daily for years. With a current market value of approximately $9.45 billion daily, adequate capital should be needed for transportation system development. A rocket/reentry vehicle system must be improved to fulfill this transportation need. Griggs (Griggs, 2024c) defined new space elevator requirements for industry technology development that targeted a 400-600 metric ton lift capacity to geosynchronous orbit (GEO). The same space elevator-sized tether system could transport the 640.7 metric ton down-Earth needs of the space settlement repayment shipments. As described, one slightly oversized space elevator or two smaller ones can bring back mass daily. At this stage of space elevator development, new tether materials constructed from graphene will influence space elevator sizing and design to support large mass bring-back. Technical solutions are on the horizon and can fit within the timelines of space settlement in the next several decades. It is imperative that a different non-rocket access to and from space be developed and deployed for a space-based economy truly.

Summary Paying for Space Settlements

Space settlement is a technical and costly endeavor. Considerable effort has been expended on space's technical and scientific aspects, from survival to physiological to psychological. More needs to be discussed on how space settlement is paid for based on Earth-supplied transportation, goods, and equipment

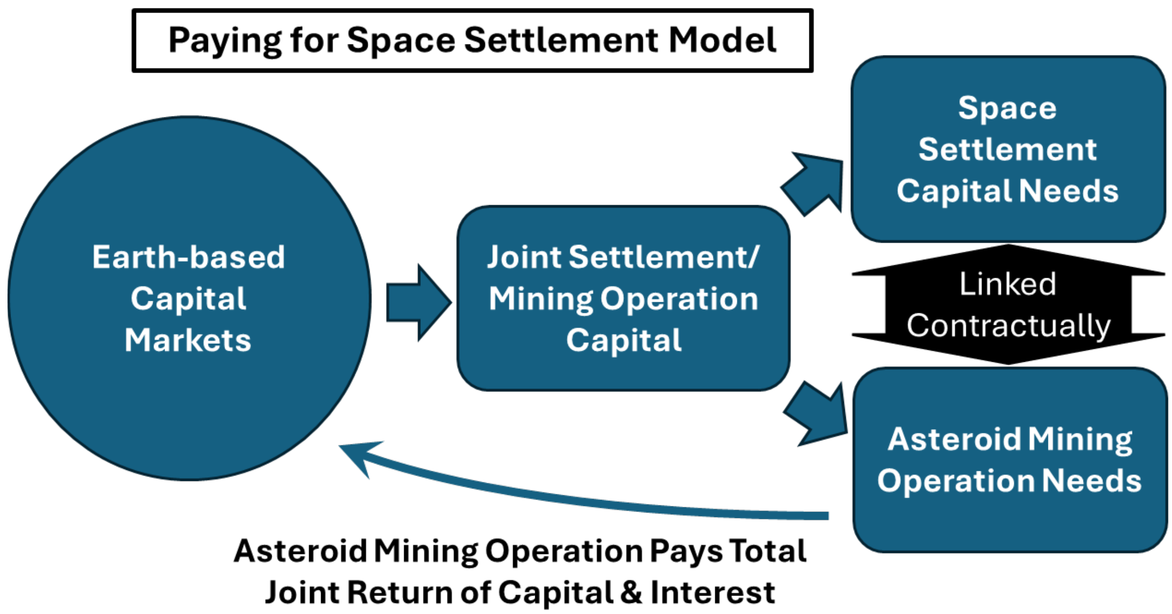

Figure 10 Paying for Space Settlement Financial Model Requires Joint Asteroid Mining Operations.

for the settlers. This paper presented an ISEM that is novel in linking an asteroid mining operation to a space settlement, whether collocated or not, Figure 10. The mining operation would pay the settlement cost and provide low-value construction materials for settlement facilities on Mars or possibly include large space stations as described by O'Neill (O'Neill, 1976).

Various economic and technical challenges were identified that require additional research and development. Uncertainty of the actual asteroid's exact rare-Earth material composition and commodity markets response to a future influx of PM and PGM far more significant than current annual global production will affect payback periods and residual PM and PGM to remain in space for other applications.

The concepts described in this paper are a starting point for identifying a method and system by which space settlement can be paid, even considering the trillions of dollars required. The capital required to settle space will only be available from the $256 trillion global capital markets with a payback plan. The exact legal, contractual, technical, and investment details can develop over time. The importance of creating a system by which space settlement is financially achievable will allow dreamers to become settlers. The economic uncertainty and possible outcomes should be explored using current complexity economics theory and analytical concepts. New models and techniques for evaluating complex adaptive systems should be explored and evaluated using traditional economics and complexity economics to better understand the possibilities of how the space economy may develop over time (Beinhocker, 2007).

The author will continue other missions and economic assessments concerning space mining and the space economy. Earth-based economic theory will be assessed for its applicability to the space economy. Modifying theory and new economic theories will assist in understanding investment recovery, individual income, settlement income, and all the various aspects of a capitalist-based economic system. An acceptable risk-adjusted rate of return will also have to be determined, which is adequate for capital markets and incentives for mining operations. Socialistic and communistic systems do not incentivize humans to perform to their utmost (Borjas, 2005).

It was also argued that a different non-rocket access to and from space developed and deployed for a space-based economy. Rocket-based solutions are limited in outbound transportation and have almost no bring-back capability for returning wealth to the Earth's surface to pay for space settlement. Without a non-reentry vehicle and rocket solution, large-scale space settlement and economy beyond LEO is just a dream.

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