Changing the economic paradigm for building a space elevator☆,☆☆

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A B S T R A C T

The development of the traction Space Elevator concept started in 1959 with Yuri Artsutanov. From an early stage, researchers identified the traction cable or tether as the technical bottleneck of this space infrastructure, and it has marked the rhythm of its development. While this technical approach has generated great benefits, moving ahead with the product design and architecture, it has left out other important areas, such as the potential economic impact of Space Elevators. During Bradley Edward's studies for NASA in 2002–2003, the economic scope was only covered on two points: the estimated cost analysis for its construction; and how its cost per kilogram compared with rockets. The economics of Space Elevators has not progressed much since then, and new papers either refer to the 2003 paper or update the data of these exact two points. With the current global trends favoring a burgeoning space economy, it is even more crucial than ever to develop a long-term sustainable economic overview for Space Elevators to accelerate the development of this megaproject.

This paper analyzes the economics of Space Elevators as infrastructure and a platform, utilizing relevant historical examples, such as the standardization of shipping containers, the transcontinental railroad, and the Panama Canal to explore its economic value and developmental impact. Infrastructure, at its core, provides value through the reduction of transaction costs. Therefore, trying to close a business case for infrastructure by charging high transaction costs is a doomed venture. However, expanding the picture to view the impact on the economy from increased access to value and more efficient markets through lower transaction costs and infrastructure becomes a very lucrative, stable, and reliable investment. Cost per kilogram is the language of rockets – strategic investment, ubiquitous access, and uninterrupted exchange of resources are the staples of Space Elevators.

Space Elevators are an evolution of launch technologies. Rockets are capable tools to lift payloads to orbit, including human cargo, but they are impractical tools for the mass quantities, distances, and timelines needed for our ongoing space ambitions. The focus of this paper is on establishing the value of a Space Elevator as part of a larger economic ecosystem and using that foundation as grounds for acquiring the financial leverage that will be required to construct it. To achieve this target, this paper presents a roadmap for the business development and financial milestones along the path to building this megaproject.

1. Introduction

Space presents humanity with the next potential industrial revolution. In order to achieve the great ambitions, we have for space development, we need more than rockets ferrying small loads into space, one at a time. A Space Elevator is not just a new way of getting to space, it is a new way for humanity to be in space. With a Space Elevator, we can build cities, colonies, and constructs not yet imagined.

Building a tower to the heavens has been part of human ambition as far back as antiquity and the legendary Tower of Babel. Five decades since the moon landing, we now have the potential to take these dreams of climbing to space off the pages of history and onto the spreadsheets of investors. A material strong enough to build a Space Elevator has been created that is in development for scaling production to the scope of this project. This paper is about transitioning from the dreams of a Space Elevator to an investment proposition for building one.

Massive infrastructure projects such as this are often hailed as great successes in hindsight and wonders of the modern world, but when they start, they are consistently undervalued and considered a waste of money. Investors with the foresight to invest in these projects and take advantage of the opportunities they create have become some of the wealthiest individuals and strongest financial institutions ever built. From JP Morgan's investments in railroad to Silicon Valley investors who funded the rise of the internet infrastructure, these individuals are not only wealthy, but powerful in determining the direction of development.

Previous analysis of a Space Elevator and other grand megaprojects focus on the high cost of these feats of engineering. Indeed, a Space Elevator is projected to cost $10–20 billion dollars (up to $100 billion for a human-rated design), but from the perspective of the global investment market with more than $200,000 billion in accounts under management, governments with annual infrastructure expenditure in the trillions, or even the illustrious class of space billionaires and their capital raising efforts, a Space Elevator's cost may be a factor, but it is far from the most critical aspect of getting it built.

The current paradigm for building a Space Elevator incorrectly focuses on cost per kilogram, a metric only relevant to rocket services. Instead of focusing on the consumer perspective, we need to reframe Space Elevators from an investment perspective. A Space Elevator will require institutional scale investment and to attract that funding, it will need to speak the language of investors: profits. As with any business venture, it is not about how much it costs to do something, but how much it makes, namely: how long until it generates a return of investment, how much it makes as a return on investment, and how much risk is there in the project succeeding. Therefore, to build a Space Elevator we need to be talking about value, cost, and risk, not just consumer price, to secure financing.

This paper begins with a literature review establishing the context for what a Space Elevator is, why it is relevant, and what problems remain. The methodology breaks down these problems and how this paper will analyze and address them. This section presents an inequality for evaluating a Space Elevator and similar investment opportunities as a shift away from cost per kilogram comparisons. Then, the analysis section will do a deep dive on the value, cost, and risk of a Space Elevator. The discussion section will use those results to produce a road map for the future development of a Space Elevator system and for procuring the necessary funding.

2. Literature review

This section will cover the historical review of Space Elevators and the public and private initiatives to build one; the contextualization to understand the value of Space; the tether material as the major technical constraints of the project; and a description of Space Infrastructure. These four concepts will provide the foundation to define what is needed to fund and build a Space Elevator and what are the most important focus areas to increase the chances of the project becoming a reality in the near future.

2.1. Historical overview of Space Elevators

Since the Tower of Babel, humanity has continued to dream about a tower to space, well before the invention and use of rockets. In 1895, Konstantin Tsiolkovsky was inspired by the Eiffel Tower and the wonderful demonstration of steel in graceful logarithmic curves and imagined a similar tower built to space [1]. Yuri Artsutanov conceived the modern Space Elevator when he envisioned it as an exceptionally long cable in traction. Rather than building up from the ground like a tower, his design for a Space Elevator is based on housing the center of gravity in geosynchronous orbit and extending a long tether down to Earth and a smaller one up to a large anchor (like an asteroid). The force of gravity pulling the tether down to the Earth would exactly balance the

centripetal force pulling the tether outwards as the Earth rotated it like a ball being spun around on the end of a string. The entire tether would be in tension holding these two forces together and allowing an elevator climber to traverse up and down the tether like a giant vertical railroad to space over 100,000 km long.

At the time, a material strong and light enough to hold its own weight was impossible. Because the mix of extreme strength and low density is fundamental to such a tether, a new SI Unit 'Yuri', shown in (1, was created to compare different material's specific strengths more clearly [1].

$$1 \; Yuri = \frac{1 \; Pascal}{\frac{kilogram}{meter^3}} = \frac{1 \; Newton}{\frac{kilogram}{meter}} \qquad (1)$$

The idea for a Space Elevator in traction was further refined by the late Jerome Person, who provided countless calculations of its design and operations, bringing quantitative requirements for the tapered tether and several other components. Working with Jerome, Arthur C. Clarke popularized the concept in his seminal work Fountains of Paradise, even coming close to the mark with 'pseudo-one-dimensional diamond wire'. In 2003, Bradley Edwards (working at NASA), did a feasibility study on Space Elevators based on the new innovation from 1991 of carbon nanotubes (CNT), which was the first material tested to achieve enough mega-Yuri (about 130) to be a viable tether material [2]. This study is thorough and detailed and has been heavily cited and utilized in further refinement of the Space Elevator concept. As a result of this feasibility study, Edwards found that if CNT could be scaled, then a Space Elevator would be able to deliver mass to space at ~$100/kg, far less than the contemporary alternative of the Space Shuttle costing $54,000/kg. This generated a lot of hype and there were several major attempts to design a Space Elevator using CNT between 2010 and 2018, including GoogleX, NSA, ESA, PrizeX, Obayashi Crop, and the Chinese Government [3,4]. Unfortunately, CNT has yet to be scaled effectively, with strands reaching only about half a meter after two decades of development–a far cry from the 100,000 km needed.

The International Space Elevator Consortium (ISEC) was created to bring all the minds working on the Space Elevator problem together and collect the above ideas into a new action plan. However, the literature that delves into the geopolitical, physics in space, and economics has not been progressing at the same pace as the technical solutions, despite the importance to ensure its potential implementation.

2.2. The seven major value streams for space

Space is massive – even compared to the vast expanse of the 'New World' encountered during the age of colonization. The opportunities for expansion and growth in space are unthinkably large. Trying to quantify a figure for potential value, however, is not especially useful. The potential value is nothing more than an astronomical figure until work and investments are made to leverage those opportunities to create meaningful value.

While the exact valuation of space is of little practical use, categorizing the distinct kinds of investments in space is useful because it can guide both financial and revenue models which are well suited for each investment class. There are broadly seven categories of space value streams:

1. Launch/Access to Space
2. Science
3. Communication/Remote Sensing
4. Constructs
5. Extraction
6. Enterprise/Trade
7. Existential

At present, the first three points (Launch, Science, and

Communication) represent the lion's share of investment in space [5]. These three alone account for most of the $1 trillion 'space economy' projected for the 2030s [6]. All three are primarily focused on providing direct benefit to Earth in the form of useful observations, research, and access opportunities.

Constructs are the physical place where all seven of the value streams will be developed. At present, the only foothold we have in space is the International Space Station (ISS) and it is one of the most expensive objects humanity has ever produced [7]. The ISS, serving as the longest operational platform in space, is just starting to scratch the surface of construct value. Recently, commercial interests like the Bishop pod, the spaceborne supercomputer, and the Orbit fab space tank, utilized it to demonstrate their value [8–10]. The Chinese station [11], Axiom Space, and Nanoracks outpost programs all have even more plans to expand into this new category. SpaceX is seeking to start building a base on Mars, a foothold on another world entirely, to eventually build a city for more than a million people [12]. Blue Origin has even grander visions of developing an O'Neill cylinder in space that could support more than 10 million people at the L1 LaGrange point [13].

Extraction is perhaps the most easily grasped of the potential value streams in space, and yet so far it is little more than a scientific curiosity. Aside from the obvious value of the resources themselves, due to the high cost of lifting mass into orbit, even mundane and abundant commodities on Earth are highly valued in space. The US and China both have a direct interest (and plans) for landing on the moon to extract and utilize lunar regolith for silicon, ice/water/fuel, and helium-3 production [14,15]. SpaceX intends to use the Sabatier process to derive methane from the CO_2 in the Martian atmosphere to generate enough fuel to make a return trip to Earth [16].

Beyond massive celestial bodies, the Japanese have successfully collected asteroid samples and aspire to eventually use that data to extract significant value in future mining operations [17]. The estimated potential mineral value of just near-Earth asteroids, based on the presence of platinum-group metals (gold, rare-earths, and other heavy metals), is more than $222 trillion at current market values [18]. On the other end of the spectrum, 16 Psyche, one of the larger asteroids in the asteroid belt, is due for physical examination by NASA and has an estimated iron value of $10 quintillion, or about seven orders of magnitude larger than global GDP [19]. Space solar power (and transmission to Earth) is itself a form of extraction not yet tapped, but can provide trillions in electricity generation in the coming decades and even surpass all terrestrial power generation capacity [20].

As traffic and utilization of space increases in the coming years, activity will start to transition from an exploration/recon mission focus to one where commercial enterprises and trade dominate the market. SpaceX, Rocket Lab, and others have been leading forces for the last decade in transitioning access to space to a commercial service, including resupply for the ISS [21]. Jeff Bezos and Richard Branson both earned significant notoriety in 2021 for being the first billionaires to travel to space, and both have generated significant interest and pre-orders for future commercial space hops [22]. SpaceX intends to send Yusaku Maezawa and eight artists to the moon on the first trip around the dark side of the moon, traveling farther than any humans before them from planet Earth [23]. This commercialization of space into saleable services will accelerate as new opportunities unfold. Fuel depots, satellite repair/deorbit services, space tugs, and CIS lunar delivery all are in preliminary stage development and are set to expand with the Artemis program. Its target is to land on the moon in 2024 (now delayed) and start building a long-term lunar base [24].

The last category, existential value, is difficult to define economically but has two major benefits: inspiring humanity and the preservation of life itself. President Kennedy's 'We choose to go to the Moon' speech rallied the American people in a race with the USSR and fostered a generation of engineers, educators, scientists, writers, cultivated a space mystique, and so much more [25]. This pent-up energy eventually led to the moon landing in 1969 and the most widely anticipated and viewed event in human history [26,27]. The achievement was a victory for all humanity. The existential value of space is its ability to bring us together with a common goal, to inspire innovation that reaches far beyond the space economy, and to give humanity a greater shared destiny to pursue together.

As for the second existential benefit, Elon Musk has repeatedly stated the importance of 'making life multi-planetary; ' indeed, it is SpaceX's mission statement [12]. Intelligent life in the universe may or may not be unique, but it seems to be exceedingly rare. The old adage to 'not keep all our eggs in one basket' is critical when considering how to best protect the rare and beautiful spark of intelligence we have on Earth. Spreading humanity and life into many space stations, bases, planets, and one day the stars is the best way to preserve our legacy. The existential value of space may not be as tangible, but even compared to the other six massive opportunities, it may be worth the most.

The path forward to reaping the immense potential value of space from all its many value streams is only waiting on our ambition, investment, and execution.

2.3. Tether material options and constraints

The material required for the Space Elevator tether needs to be both extremely lightweight and strong to hold its own weight and carry cargo. The unit to measure the tensile strength per unit of density is called a 'Yuri,' as was described in the historical overview. Today's super strong materials, such as Kevlar, are still two orders of magnitude below the requirements of the Space Elevator [28], meaning they are too heavy to function as the tether material. In the 2000s, new one-dimensional (1D) and two-dimensional (2D) materials were invented in the laboratory that would be able to have the level of Yuris required for building a Space Elevator. Three materials are currently under analysis by different workgroups across the globe: 1D Carbon NanoTubes (CNTs), 2D single-crystal graphene (Graphene), and 2D Hexagonal Boron Nitride (hBN). Each of them has specific challenges ahead before they can achieve the mass production required to build the 100,000 km-long tethers of a Space Elevator.

CNTs have gained a lot of popularity during the mid-2000s for the space industry and the Space Elevator community, led by Bradley's Space Elevator assessment for NASA in 2001–2003 [29]. The Yuri characteristics of this material increased the hopes of being able to finally build a Space Elevator and it led to feasibility research and competitions by public space agencies such as NASA, ESA, and JAXA, and by private entities such as Xprize [30] and the Obayashi Corporation. At that time, CNTs were still in the early days of development, and it was not clear how possible it would be to build 100,000 km long CNTs threads. As of today, the longest CNT ever built was one-half a meter in 2013 [32], causing most of the frenzy for CNTs applied to Space Elevators to fade away by the mid-2010s. However, there are still some initiatives on this material coming from the Obayashi Corporation, which has been testing CNTs in space from the International Space Station (ISS) since 2016. The initial tests showed a degradation of the specific strength (Yuris) for pristine CNTs by 40–65% after exposure to Space [33].

Graphene and hBN fall in the category of relatively new 2D materials with high enough Yuri scores to be possible candidates for a Space Elevator tether. While they have existed for more than a decade and more than a century respectively, their industrial applications are still in the early days. hBN hasn't been produced yet in large quantities, and graphene production in "roll to roll" configuration is still only produced for the electronic industry in its modality as "polycrystal graphene" at the speed of 1 m per minute [28], These "polycrystal" configurations have impurities between groups of molecules that decrease the optimal characteristics of the material. While these structure impurities are viable for its requirements in the electronics applications, they cause it to fall short of the Yuri requirements for a Space Elevator tether. Graphene development continues to happen extremely quickly and new

methods both publicly and behind closed doors require very up to date assessment for calculating risk.

The development of CNTs for a Space Elevator during the last 20 years shows how difficult it is to bring one material from a laboratory all the way to testing and production, highlighting the setbacks that may happen during the process, such as the degradation of specific tensile strength and the limited ability to produce long threads of the material. While the two 2D materials presented seem more promising from a manufacturing perspective, the engineering validation and tests are still to be made and passed. The materials need to be produced and maintained in their purest form as a single crystal over thousands of kilometers without any significant defects [28].

Finally, it is important to highlight the challenge associated with the required massive volumes of tether material required. It is estimated that a Space Elevator with 2D materials would require around ~14,000 layers of these materials in a continuous layer, each 1 m by 100, 000, 000 m in size. To put it in perspective, a single layer of Space Elevator material would be equivalent to 250 times the total production of aluminum foil for Europe in 2019 [28,34]. While the raw material cost and total mass for the tether are trivial compared to aluminum foil, this comparison demonstrates the level of production growth that would be necessary to scale production. Millions of kilometers of this material still need to be proven viable in mass production, manufactured at an industrial scale, and validated for atomic-level precision in sheet uniformity.

2.4. Considerations for space infrastructure

One of the chief differences between land infrastructure and space infrastructure is that objects in orbit are constantly in motion. There is little risk of the London Bridge being moved, stolen, or slamming into Paris, or that pebble-sized rocks in the area might impact it going 17,000 km per hour with the kinetic energy of a large bomb [35]. Therefore, infrastructure in space presents significant challenges to how structures will be built, managed, maintained, and protected.

Space also has a unique legal framework which is still being developed and refined. The specific implications of these debates and their outcomes are outside the scope of this paper, but the context is referenced here because it is critical to the development of a space economy and in defining how, and by whom, space and its resources can be used.

The foundation of international space law is the Outer Space Treaty. When the Outer Space Treaty was initially drafted, largely between the USSR and the US, it was debated whether to model its legal framework on the airspace or marine domains while simultaneously negotiating terms relevant to national defense, national interest, and with limited knowledge of future applications in a very new domain [36,37]. The then-recently drafted Convention on the Law of the Sea was chosen in large part to avoid the creation of a *casus belli* (an action or event that provokes or can be used to justify war) by allowing satellites to freely travel over enemy territory. Based on a similar precedent for naval merchant vessels, "… freedom of navigation and overflight solely for the purpose of continuous and expeditious transit of the straight between one part of the high seas … and another part of the high seas …" as opposed to more strict airspace border enforcement [38].

A second foundational source for the Outer Space Treaty was derived from the also then-recent Antarctica Treaty, which set aside all of the continent for peaceful, scientific purposes [39]. All three of these frameworks draw on legal concepts from an older Roman Doctrine with the Latin title *Res Communis*, which formalized the concept of 'the commons' – lands not owned but managed publicly [40]. One of the main mandates of current space law is "the exploration and use of outer space shall be carried out for the benefit and in the interests of all countries and shall be the province of all mankind" [41]. The degree to which the original Roman roots still constrain space law, the grey areas regarding the explicit restrictions on nation-states, and how much they apply to private enterprises is the subject of continuing debate [40,42,

43]. This creates potential barriers to the development of more complete property rights regimes and the establishment of 'permanent' structures in space or on celestial bodies.

Outside the Outer Space Treaty, national space policy and bi/multi-lateral agreements also shape customary space law. Notably, the US Space Resource Exploration and Utilization Act of 2015 and the 2020 Artemis Accords support the idea that any extracted space resources are the private property of the entity that obtained those resources and that their extraction "does not constitute national appropriation [which is not permitted] under Article II of the Outer Space Treaty …" [44,45]. These interpretations of the Outer Space Treaty support the use of space resources and establishing 'safety zones' for local operations. In another vein, the Intergovernmental Agreement operating the International Space Station affords its signatories the ability to use, maintain, and extend jurisdictional control over their modules in accordance with the Outer Space Treaty [46]. These additions/interpretations of space law are supportive of the idea that a space elevator is neither an appropriation nor has ownership of the space it occupies—furthermore that its occupation of space is protected under the 'explore and use' clause in Article I of the Outer Space Treaty.

Further research and investigation into contemporary examples of space is needed for the legal development of a space elevator. Two upcoming case studies include Axiom Space's notional space station and Blue Origin/Sierra Space's plans for Orbital Reef. Additionally, greater clarity is needed on the transitions between international waters, airspace, and the outer space domains a space elevator will necessarily traverse; a space elevator's interaction with objects in orbit; and the introduction and use of any non-Earth derived materials regarding use and ownership in space.

3. Methodology and framework

This section will cover the problems with the historical Space Elevator economic justification, propose an alternative framework, and highlight the underlying economics behind this replacement.

3.1. Analysis of the problem

In Bradley Edwards' paper in 2006, the economics of a Space Elevator was presented with three major assumption flaws [2]. These problems are further compounded with the many citations of this paper and through interpretations that missed some of the nuances in the original description. This paper seeks to overcome those problems by first identifying these oversights and how they impact our understanding of a Space Elevator as a foundation to better identify and describe its merits.

First problem: presenting the Space Elevator from the perspective of a consumer rather than as a developer or investor. Cost per kilogram has been the metric of value for why a Space Elevator is valuable. This model is based on comparing two transportation options, like a plane or a bus. Each method of transport is treated as a service, where transaction cost of one is weighed against the other in terms of speed, safety, price etc. When the paper was published, the cost of using the modern option of the 'reusable' space shuttle was more than $54,000/kg, while the Space Elevator was loosely projected to cost less than $100/kg [7]. In the 18 years since, this line of reasoning has significantly weakened because the cost of rockets has fallen dramatically. As of mid-2021, the Falcon Heavy was the least expensive path to space at only $1400/kg, already one-fortieth of the price of the space shuttle, but SpaceX's new Starship is targeting a long-term marginal cost of only $10/kg with an opening price around $100/kg [47]. But no matter how low the cost of a rocket falls, it is still not a compete argument for an investor/developer any more than a cheaper bus vs plane ticket is an argument against building an airport.

Second problem: a space elevator system is not like a rocket. The metric of Cost/kg is both misleading and inappropriately applied in this

scenario. Generally, rockets use this metric to compare the cost to low earth orbit (LEO), and while a space elevator technically goes through LEO, it is not traveling at an orbital velocity in LEO. A space elevator, by design, is traveling at an orbital velocity only in GEO and its 'cost' to space is almost height independent. Meaning, the cost to get to LEO is materially almost the same as the cost of departure from the apex anchor, which is both vastly more useful and extremely difficult to replicate with a rocket.

Third problem: presenting the Space Elevator as an enterprise selling a service rather than framing it as an infrastructure development project. This problem is the most nuanced of the three. Evaluating these two options on a Cost/kg basis as an alternative to the service rockets provide misses several critical investor benefits, including throughput scaling, economic development opportunities, and mass-independent launch profiles made possible with a space elevator infrastructure construct. Furthermore, while it is economical for all ventures to lower their operational and marginal costs, enterprises and infrastructure have different incentives for determining value. An enterprise is incentivized to raise prices as high as the market will bear, balancing supply and demand to maximize its profit. Whereas, a successful infrastructure project is incentivized to maximize utilization, which requires decreasing the price for the consumer as much as possible including subsidizing the cost entirely.

The economic paradigm of building a Space Elevator needs to shift from a focus on the cost to the consumer to a focus on its value to the investor. In infrastructure, this paradigm shift is especially important because the value of infrastructure comes from a reduction in transaction costs to increase the rate of utilization and thereby enhance economic productivity. To an investor, a Space Elevator is far more valuable as a departure point to the solar system and harbor for interplanetary trade than a business fighting to generate profit from selling ever-cheaper tickets to space. The true value of space is not based on merely reaching space, it is in what can be done once there. A Space Elevator successfully addresses six of the seven major value streams for space development and creates a launching platform for extraction efforts (the final value stream) anywhere in the solar system.

3.2. Evaluating economic opportunities

For any given investment opportunity, the following inequality must hold true to entice investment funding.

$$Value \gg \frac{CapitalCost + Financing}{Political \times Social \times Market \times Technical\, risks} \qquad (2)$$

The value on the left side represents the value created and made available from the development of a Space Elevator. Throughout this paper, we will consider many different potential values, including moving mass to the different layers of Earth's orbit and beyond, as well as the services provided by a galactic harbor. Some values of space, such as the price of satellite placement, are easily quantifiable, while other values, such as the mining and extractive value of asteroids, are more difficult to quantify. Therefore, this inequality is not designed to generate a specific numerical value, only give context to a potential investor. This ambiguity is tolerable because if the left side of the inequality is perceived by an investor as being much greater than the right, then it represents a good proposal and until the difference is sizable, investment is unlikely, given the number of unknowns, high cost, and long timelines for development.

The right side of the inequality to which value is being compared is the risk-modified capital cost. This cost involves three elements: the capital costs themselves, the cost of financing, and the risk modifier. There exist several different cost estimates for the capital investment necessary to build a Space Elevator, depending on several factors, including materials used, the construction approach, and technical requirements. This paper does not attempt to establish a specific, reliable capital cost, but to work from a general range of reasonable orders of magnitude.

The cost of financing includes all additional costs necessary to secure and repay the initial capital cost. It could become an important value or even the largest cost overrun on complex infrastructure projects [48,49].

The final element in the denominator on the right is risk, which is described in four general categories: political, social, market, and technical. As with the other aspects of this inequality, the purpose is to have a metric to determine when an investment in a Space Elevator becomes viable. These four risk categories represent the total failure conditions based on the likelihood of success, with ratings between 0% and 100%. Meaning, if any one of the four risks has a 0% chance of success, then the investment is made non-viable at any cost.

3.3. Linear price reductions cause exponential growth

Many infrastructure projects have the dubious honor of appearing as amazing investments in hindsight and overpriced boondoggles in the present. This contradiction is largely explained by the chronic underestimation of how linear reductions in price lead to exponential increases in use. A prime example of the effect of a price decline leading to exponential growth is the aviation sector. In 1941, aviation was an exotic affair. As shown in Fig. 1 flights were both monetarily much more expensive and much less convenient [50].

Few people had the luxury of flying and the most common flights were from 'flying aces' in the armed forces. Fast-forward to 2015, and flying was faster, cheaper, and more convenient, allowing most Americans the opportunity to fly, sometimes many times a year. Yet while the price has fallen to about one-tenth the price, utilization as shown in Fig. 2 has increased more than 8500 times [51].

This phenomenon is not unique to aviation. Multiple times throughout history, small reductions in cost have directly led to massive increases in use and the creation of new viable market opportunities. Economic booms, from expansion to the New World using cheaper ships and better navigation techniques, trade between Europe and Asia with the completion of the Panama Canal, and the expansion of cities along new tram lines provide but a few examples [52–55]. Price reduction is not unique to infrastructure, but as identified in Section 3.1, price reduction is a major source of value for infrastructure projects like a Space Elevator and antithetical to profit-driven enterprise.

4. Analysis of the value proposition

This section explores in detail the investment opportunity inequality. Breaking down the problem into chunks, the value of a Space Elevator and comparison to the value of rockets is described to establish the left side of the inequality. Then both the top and bottom of the right side of the inequality are fleshed out to better identify the most important factors in the risk-adjusted cost. Altogether, this analysis aims to highlight the current strengths, opportunities, and weaknesses in the value proposition for building a Space Elevator.

4.1. Unique value drivers of a space elevator

The value of a Space Elevator is much more complex than the monetary value of providing the service of delivering mass to space. As observed in earlier sections, infrastructure increases economic productivity and value causes exponential expansion, as price falls and utilization rises. A Space Elevator creates far more value serving as the backbone to space, connecting burgeoning economies together, than it can relying on transportation revenue. The transcontinental railroad across the US fundamentally changed travel and led to millions of new jobs, homesteads, and the foundation/growth of several large cities, including Denver. But despite this success, the companies that built the railroad went bankrupt within a decade of its completion [56].

The International Space Elevator Consortium has created a working architecture model for a Space Elevator which is shown visually in Fig. 3
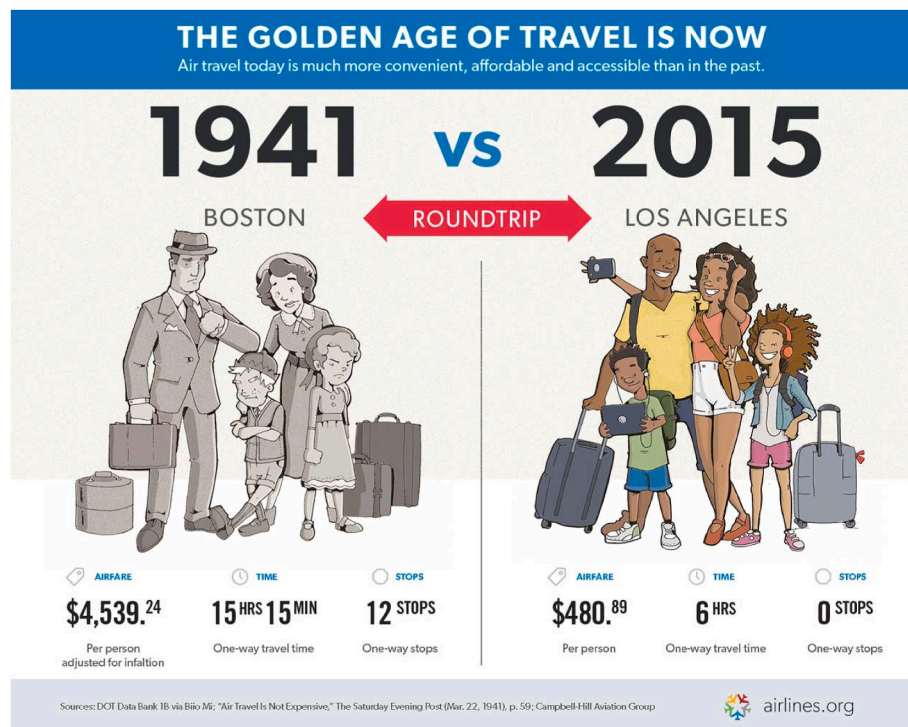
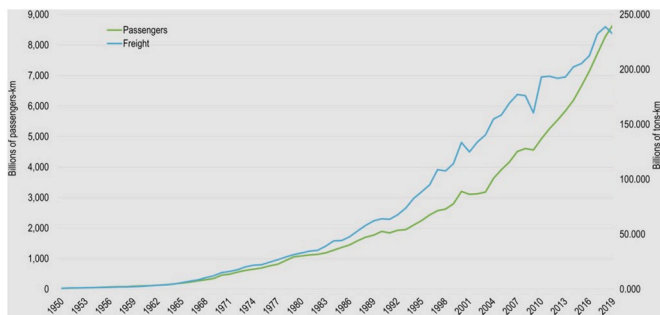**Fig. 1.** Changing cost of airline flights.

Fig. 2. Increase in passenger and freight air traffic.

[57]. This framework is useful for showcasing how a Space Elevator is like a giant trellis which serves as a foundation for growing a more robust space economy. The following sections give a glimpse into the many unique opportunities a Space Elevator system provides, alongside its baseline function of facilitating the transfer of mass along the 100,000 km long tether.

4.1.1. Earth Port

The Earth Port, the base anchor of the Space Elevator, has several functions as described in the 2020 ISEC Report [57]. It serves as the naval harbor for accepting and transferring ocean-faring goods to (and from) the Space Elevator while a nearby Headquarters and primary operation center facilitates the logistics of goods flowing through the port and up the elevator. As a major ocean port, it also serves as a refueling port, transfer hub, and even a small artificial city.

The Earth port functions much like classical harbors and large terrestrial ports in major cities today – except instead of connecting to metropolitan regions and cities, this port serves as the main channel for access to space and the solar system at large. In 2020, the global satellite industry generated $271 billion in revenue, despite only adding 697.6 tons in mass to orbit (about 500 tons to LEO) [5,58]. Comparatively, the San Pedro Bay Port Complex in Los Angeles, representing 74% of west

coast trade in the US, facilitated the transfer of $259 billion in cargo or about the same financial throughput [59]. Even at initial operational capacity, the Space Elevator will be able to transfer over 5000 tons up to GEO and beyond annually and its throughput only increases as the Space Elevator system increases in size up to 170,000 tons annually at full operational capacity on the latest designs projections [57]. These figures are quite large compared to today's launching capacity, but demand far in excess of even these figures is already envisioned: 5+ million tons for Space Based Solar Power, ~10 million tons for just one O'Neill Cylinder, 1+ million tons for SpaceX/Elon's Martian city, millions of tons high grade nuclear waste materials, and more [60]. At these throughput levels, the Earth Port, as a terrestrial hub for the Space Elevator, would be the main channel to space, able to service hundreds of billions and eventually trillions of dollars in annual cargo flow as the space economy continues to expand and develop.

4.1.2. Galactic Harbor in GEO

The Galactic Harbor, as showcased in Fig. 3 represents both a physical node on the Space Elevator tether and a 200 km-plus wide region enveloping two parallel Space Elevator tethers. As a region, it has the potential to function much like the city of St. Louis (on the Mississippi River) did during the age of American expansion into the West. It would be the leading edge of civilization and the final stop before heading into the frontier. Most any product would be available for sale in the GEO region. Only one 'train' ride away, it would be the final stop to collect any last items or hire any assistance. This region is unique along the Space Elevator as it is the only height where objects are in classical orbit, geosynchronous, and experience effective weightlessness. As a result, there are no mass constraints from the tether in this region for the development of structures, enterprises, docking stations, fuel depots, or even shipyards destined for regions further afield. Of particular interest, Space Solar Power can utilize those relatively stationary orbital positions to transmit power to fixed locations on Earth while benefiting from near-constant sunlight [61]. Given enough time and demand, this region could develop like St. Louis or the many cities along the Transcontinental Railroad, into a thriving economy, and even a city in space.
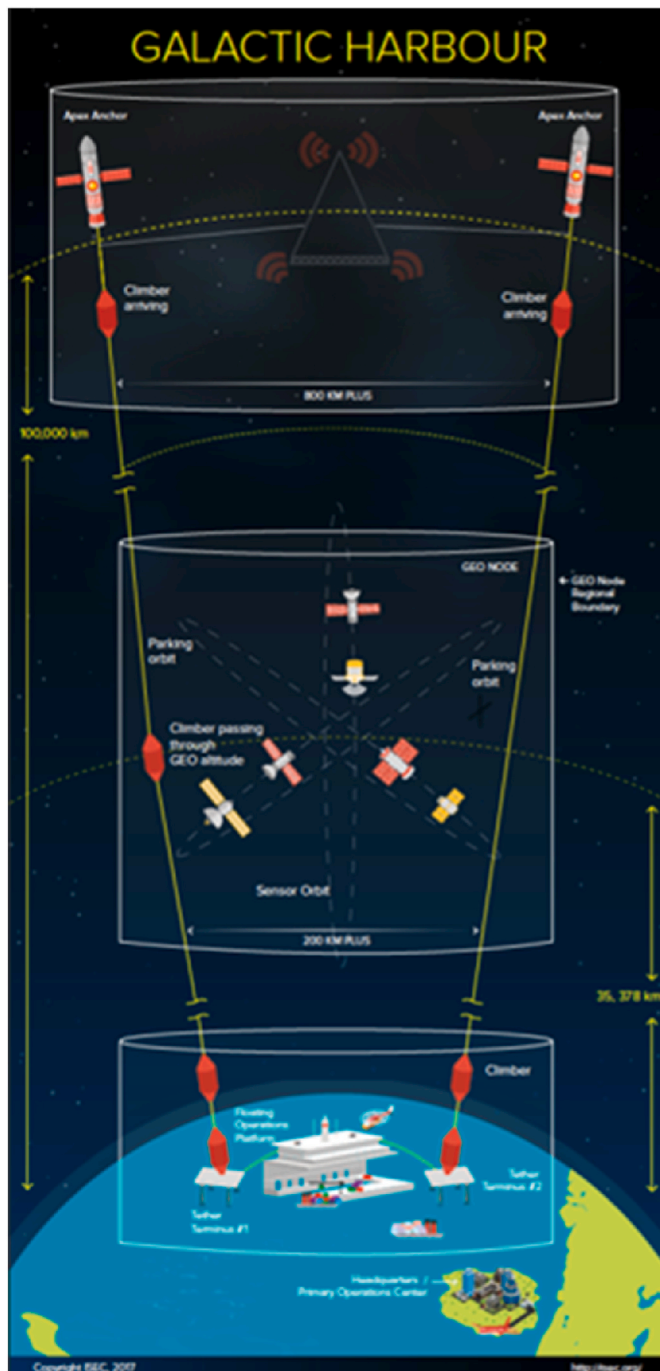
Fig. 3. ISEC space elevator architecture plan.

More than just an exit port, this harbor would be an island of safety, a lighthouse, and a base of operations for emergency services. As alluded to earlier in Section 2.4 and in many other works, space debris in orbit is a significant, if currently improbable, threat [62]. Just as the British Lighthouse system was developed, the proposed Galactic Harbor has a vested interest in protecting its users and could benefit from the same financial system of harbor fees to fund their monitoring efforts [63]. The monitoring stations aboard the Galactic Harbor and along the elevator allow them to observe, avoid (moving the whole elevator), and even commission the removal of space debris to protect the cylindrical volume around the Space Elevator.

4.1.3. Apex anchor

At the very 'top' of the Space Elevator, the apex anchor is a literal mass anchor used to reduce the tensile requirements and stabilize the tether, but its main value is as a mass-independent departure point to anywhere in the solar system and even other stars. Like a child clinging to the edge of a fast-spinning Merry-Go-Round, anyone at the Apex Anchor on a Space Elevator experiences centripetal force pulling them outwards away from the Earth. Indeed, because of the gigantic radius of the Space Elevator, the apex anchor at 100,000 km would be a small island at the bottom of an exceptionally long tether going up toward the small blue ball in the sky with acceleration equivalent to about 2/3^{rds} Earth's gravity. If you were to time your jump very carefully off the edge of this island, you would 'fall' away at 7.2 km/s (a delta-V much faster than most rockets can achieve) and could travel to Mars in as little as 78 days or depart every day of the year instead of waiting for convergence windows [57]. Matthew Peet and John Knapman have analyzed how a Space Elevator can be improved to both utilize the kinetic energy gained from sliding down the tether from the Galactic Harbor and then routed outward into a second rotating tether, correcting the ecliptic tilt to achieve a delta-v of over 17 km/s along the ecliptic plane [64,65]. This speed is enough to depart the solar system even before utilizing gravity boosts or additional thrust.

4.1.4. Inter-elevator environment

A Space Elevator is more than just a transportation system. It also will be the largest tower ever constructed and will transition through many exotic and interesting regions along its 100,000 km length. Two aspects are uniquely valuable about this framework: fixed locations above Earth, and the transition gravity gradient moving up the tether. The upper atmosphere and Van Allen belts are both scientifically interesting places but are very difficult to study using rockets, as they must travel extremely fast to reach these heights and maintain them. A Space Elevator, by contrast, is the perfect perch to set up an entire laboratory to investigate these natural phenomena from a locally stable position. As for gravity, a Space Elevator is not classically in orbit. At an elevation of 100 km, above the Karman line, a person in a space hotel or lab would experience almost perfectly normal gravity. At the height of the ISS, about 400 km above the surface, they would still feel 98% of normal gravity and would simply fall back to Earth, and hypothetically would need only a parachute or glider (assuming they had a spacesuit with rotation stabilizers) to land safely as they are not traveling at orbital speed similar to the Red Bull stunt dive from 'space' in 2014 [66].

Traveling further up the tether, eventually the force from outward rotation and reduced gravitational pull would create an effective gravity similar to the surface of Mars, the Moon, or any other celestial body smaller than Earth. These environments are the perfect testbeds for long-term habitation studies, training, and even testing equipment destined for other worlds. Labs, hotels, penthouses, sports arenas, and more could exist along the variable gravity environment of the tether. Unlike in GEO, these constructs are constrained by their mass, based on the tensile strength of the tether, but with enough material, there is no hard limit on the scale of these constructs–other than market appetite.

4.2. Space elevator value as compared to rockets

The ability to use a Space Elevator as a giant sling allowing for rapid travel anywhere in the solar system is impressive, but the ability to use it as a nearly-mass-independent system is transformational. Rockets are invariably bound to the rocket equation [57]. Accelerating larger masses or reaching higher delta-v requires exponentially more fuel since rockets must not only expend fuel to accelerate but also must provide the energy to move all that additional fuel. Reusable rockets are a fantastic development, but they cannot overcome physics. A Space Elevator, on the other hand, only has to provide enough energy to lift mass to GEO and the momentum of the Earth provides all the remaining energy to propel objects outward. As shown in Fig. 4, this linear vs exponential
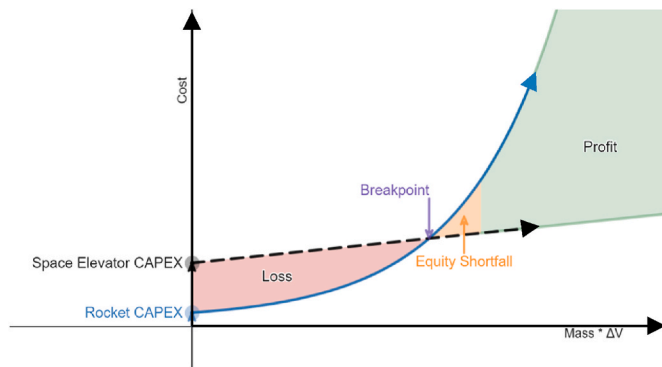
Fig. 4. Space elevators and rocket cost growth curves.

relationship inevitably results in a breakpoint where a Space Elevator is cheaper than the number of rockets required to provide the same mass acceleration. Once the Space Elevator's better margins recoup its high capital cost, all future revenue is profit over rockets. The question is not if a Space Elevator will surpass rockets, but how far out to the right (aka how much mass throughput) will humanity need to demand before the breakpoint occurs.

4.3. Capital cost and financing

There have been several estimations in the last 20 years on the capital investment necessary to build a Space Elevator, ranging from $15 billion to $100 billion, depending on the construction timeline, material availability, safety factors, and the costs of certain technologies at that time [7,67,68]. This cost range is already the most specific variable in the investment proposition inequality and this paper does not seek to update it further.

The cost of financing, on the other hand, is still very tentative and dependent on the instruments and agreements reached. This variable encompasses interest on loans, broker fees, returns to investors, and other costs associated with receiving financing. Modern infrastructure projects have a reputation of being over-budget and late. The Chunnel under the English Channel is a prime example. But rather than cost overruns and material price escalation, finance represented both the largest single cost and the greatest cost inflation over the course of the project, increasing 220% over the original estimate to more than half the final project cost [48]. The interest rate on infrastructure projects is particularly important to consider because they often run for years before any revenues are generated to offset large loans. Despite their scale and timelines, infrastructure projects are often very lucrative investments. Even in the worst-case scenario, banks expected the Chunnel to generate an 18.8% return on investor capital [48].

4.4. Investment risk assessment

The four major total-failure risk categories in an investment proposition are Political, Social, Market, and Technical. This section explores the impact and factors influencing these risk gauges. Each of these risks is subject to future scenarios that are partly unknown, so they are weighted as a probability of 'perceived risk', which might slightly change depending on the investor or the promoter of the project. The first Space Elevator must be considered as an innovative infrastructure megaproject. From a construction perspective, its innovative design has yet to be assessed at a large scale and so it will have to contend with technical viability in addition to normal political, legal, and financial hurdles. Additionally, from an economic perspective, as an infrastructure project, similar to a bridge, a harbor, or a Maglev train network, it will need creative financing to cover its high capital cost. These two contexts are taken into consideration in the analysis below. To simplify this analysis, they are all considered total-failure conditions, which are

multiplicatively related. These risk factors are both critical to the viability of a large project as total failure conditions and as modifiers to the types of viable finance models and eventually interest rates necessary for such a large project.

4.4.1. Political risk

Political risk encompasses several smaller correlated aspects, including the legality, national political support, geopolitical tension, international backing, bureaucratic pacing, and environmental or safety requirements. There is no legal or political precedent for a Space Elevator. This fact cuts both ways because while there are few restrictions on its construction, it does not have a direct legal foundation either. This legalistic grey area is far from unique for the space environment. The Outer Space Treaty of 1967 is specifically vague about ownership and jurisdiction in the Global Space Commons [41]. A Space Elevator taking up a fixed volume of space just does not fit this legal framework very well, as written. New adaptations and policies need to be created on how to govern these areas. The Earth Port node of the Space Elevator located close to the Equator, most likely far from the coast in international waters, will have its own political implications. Political support, nationally and internationally, is vital to keeping smooth production schedules and building facilities on time, which will depend greatly on the perception of it as a dangerous technology to develop or as a key geopolitical project that will provide uniquely inexpensive, frequent, and safe access to Space. Therefore, to an investor, the level of political support and which (if any) countries have a hand in a Space Elevator's development are critical to consider.

4.4.2. Social risk

Social risk, more than political risk, is more often about extremes in public opinion, sadly often without consideration for the real facts of a project. Misinformation and fear of change are often the bane of any large-scale development project. A Space Elevator will inevitably have to face many social groups concerned with ocean damage, sight obstruction, wasting resources, and whether the tether will fall from the sky. These protests have been a part of large projects in various forms for hundreds of years. The indirect social impacts will be even more important. They affect how the Space Elevator is perceived, positively or negatively, and are the "hot-topics" or current challenges of the society. Some of them today would be climate change, monopolies, wealth inequality, race relations, consumerism, and geopolitics.

Despite the risks and difficulties, the scale of major infrastructure projects also has the potential to be their saving grace. Daniel Burnam was the chief architect of the Largest World's Fair in 1893 and heavily influenced the design of Chicago, San Francisco, and Washington DC. He is immortalized in the quote "Make no little plans. They have no magic to stir men's blood and probably will not themselves be realized" [55]. The Space Elevator can inspire humanity, in the same way as did the Apollo Program. Even more, as it would provide humanity with a stable gateway to explore our solar system and beyond in ways unimaginable and unreachable today. It may even change the perception of ourselves, as it will support the creation of outposts or colonies on other celestial bodies. Luminary figures like Theodore Roosevelt, Ferdinand Lesseps, Nicola Tesla, and even the contemporary Elon Musk, have played critical roles embracing that sentiment to inspire confidence in major projects, and manage to overcome both the political and social risks, serving as catalysts to assemble all the stakeholders, initiate and complete such projects that shape the capabilities of humanity [69].

4.4.3. Market risk

Market risk is derived from two major areas: 1) the presence, growth, and size of the target market, and 2) the availability, appetite, and risk tolerance in capital markets to fund new development in that sector.

The financial funding of large projects, and the growth of new sectors like the Economy of Space, often regulate the cadence of development as the financial markets ebb and flow with changing interest rates and

business cycles [70]. Historically, markets go through a four-stage development cycle as shown in Fig. 5 (Image created based on the work of C. Perez) [70]. From an initial irruption phase, it follows a frenzy phase with an excess of investment, and the disparity between real and paper values leads to a bubble burst and a recession. After a period of recovery and it will eventually move to a recomposition phase, driven by the few successful ventures that survived the crash and need further investment to grow until the market finally reaches a stable maturity level [71]. These cycles will affect positively or negatively the speed and success of a multi-decade project such as the Space Elevator. Stable capital sources and more secure revenue sources from government contracts, anchor clients, performance-based compensation, and other mechanisms are critical to reducing all these macroscopic market risks.

4.4.4. Technical risk

The final category, technical risk, both has the most contention and is the rarest among large infrastructure projects. It covers all the research, technology, manufacturing, and operations validations required for the project to be successful and profitable. Normally, innovative mega-projects are based on proven technology that needs to be built at a much larger scale, which brings its own research needs (and several logistics and business challenges). These risks could materialize as specific technical bottlenecks that will make the project inviable, as technical breakthroughs required to make the project profitable, or technical uncertainties that will change the cost and the timeline of the project.

As explored in Section 2.3, the Tether is vitally important to the construction of a Space Elevator. Without the massive industrial scaling of a tether material with sufficient tensile strength used to fabricate the thousands of layers of the 100,000 km long tether, a Space Elevator, as currently proposed, is not possible at any price. This barrier, while formidable, is perhaps the Space Elevator's greatest opportunity. The preceding three risk categories can be mitigated, accepted, and evaluated but are in nature speculative – whereas demonstration of technical viability at scale will immediately change the balance of the Value Proposition inequality and may be the final push needed to make it a worthwhile investment opportunity.

5. Discussion

5.1. Steps to reduce real and perceived risk

Building on the four risk categories covered in detail in section 4.4, this section covers what some of the most important and urgent actions are to reduce the risk of the project and improve its viability. This is especially important as it not only reduces the risk multiplier of the investment but makes the project more attractive to a bigger pool of investors with more conservative risk profiles. These actions would need to be covered as soon as possible during the project development, and each of them will benefit from having a resolute champion that will lead them both internally and externally.

5.2. Political risk mitigations actions

- Identify Space Elevators as the clean transportation to Space, which will reduce the number of rockets.
- Convey the economics to policy/lawmakers. Not as an application but as "a road to space" infrastructure project that will boost and stabilize the Space Economy and create high-quality jobs.
- Endorse its important geopolitical advantage either on a national or an international level.
- Align with the Space Force and other agencies/groups on the safe use this infrastructure as a gateway to space and for interplanetary travel.

5.3. Social risk mitigations action

- Create a simple communication strategic plan that will gain in complexity as the project develops.
- Avoid fear on the Space Elevator design: there are no physical risks, even in case of failure, due to the lightweight of the tether. Despite being a major project, it is not a heavy or dangerous infrastructure.
- Inspire, in a comparable way as the Apollo Program or the current commercial crews. Bring the Space Elevator to specific examples and applications that people can dream of, foment the engagement of experts in all the areas that need development and all the areas that will benefit from it.
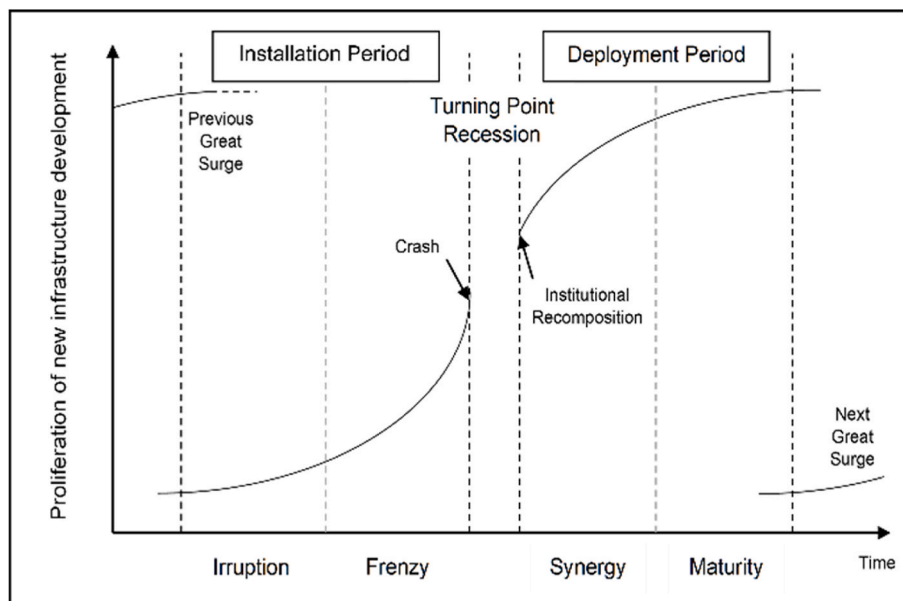

Fig. 5. Financial investment cycle.

- Analyze, adapt, and communicate how the Space Elevator affects the current challenges of society, creates the right partnerships for it, and identifies temporal and long-term communication opportunities.

5.4. Market risk mitigation actions

- Define an 'anchor tenant', the first most important customer for Space Elevator, that already has market traction, and ideally political and social hype. A good example would be space-based solar power.
- Use current investment momentum in the Space Sector, which is relevant both for the anchor tenant and for the funding needs of the Space Elevator itself.

5.5. Technical risk mitigation actions

- Project viability: Confirm 2D materials as the real engineering solution for the Space Elevator tether. With successful tests, on the ground and in space at scale.
- Financial viability: Run the necessary calculations and tests for a viable infrastructure maintenance plan.
- Project cost and timeline: confirm and prove manufacturing capability to build the Space Elevator at scale.

5.6. Financial pathway and funding development options

This section will cover four potential funding pathways for financing the construction of a space elevator: Private, Public, Public-Private-Partnership, or Internally Funded. The purpose is to evaluate the relative merits of each method based on the needs and timeline for a given developer.

As with any financial agreement, funding for a Space Elevator depends on negotiating a deal that best balances Power, Money, and Risk. These three categories are highly nuanced in every negotiation but generally: Power is the control over decisions, influence, media, employment, etc.; Money is based on how revenue, equity, salary, taxes, etc. Is distributed; and Risk is based on allocating responsibility for when things do not go according to plan (including all forms of economic, legal, and reputational plans, etc.). Motivating this negotiation is the underlying investment value position. Different proposals will have risk/reward profiles closely related to the time horizon for generating a return on the investment.

Like many evolving companies, a Space Elevator's risk/reward profile will change with development as its likelihood of success and time to revenue generation (and profits) decreases. Initially, it is a very high risk/reward opportunity when its earlier phases of project validation are still uncertain. It will transition to a mid-risk opportunity once construction of the first functional Space Elevator (based on a proven material) commences. Finally, it will transition to a low-risk investment profile as the project goes into an operation and expansion phase with stable revenue generation. Each phase, roughly described here, presents a variable investment opportunity to different investment and financial instruments with higher or lower risk tolerances and appetites.

Considering the private approach, a Space Elevator development team could form a corporation and seek external investment through different financial rounds. With each successive round of successful execution, the corporation's valuation would increase as the project uncertainties get validated, producing a large equity growth for all investors. Investors would have the opportunity to exit or increase their positions in each funding round, bringing liquidity, and steadily drawing in a wider pool of investors. The financial needs of the project will be initially covered with this high-cost equity capital and then once it becomes more stable, utilize a mix of capital and debt. It would have to balance the benefits of additional leverage with the capital dilution for its shareholders. The main flaw of this approach is that a Space Elevator, as an infrastructure construct, would not make a very profitable stand-alone business. It requires a more creative revenue generation model

than ticket revenue to be a viable option. Generating a profit from a large and growing audience can be a viable business model, even if the marginal price for consumers is free. A good example would be YouTube, which is a major digital infrastructure that hosts videos and subsidizes its costs by leveraging itself as a major advertising platform embedded in its video content to generate huge profit sharing with content creators on a free service [72]. This pathway is quite straightforward and may be a faster and simpler initial development (if it manages to attract the right initial investors), over having to collaborate with national or international groups all along the way. Conversely, because it is outside this system, it might face political and legal challenges from national and international entities as it develops.

If the project were fully publicly funded, either under a national or international organization, the project would normally start with public grants, linked directly or indirectly to some universities and research centers, to solve the most important technical uncertainties of the project. From there, an organization will be created to manage the construction of the first demos that will collect money from the public entities and it will manage the procurement and future service contracts to private entities that will develop the manufacturing and construction capabilities to build and deliver the demos at scale. The organization could control the project design and make calls for contracts for each of the components. Such a model was made for the Apollo Program and the ITER energy project. This project could be framed as an important collaboration project, aligned with UN Sustainable Development Goals (UN SGDs) for facilitating the provision of affordable, clean energy and industry innovation and infrastructure, or it could be framed as a geopolitical project to protect the interest of a nation or group of nations in their access to space. This pathway's biggest challenge would be the dependence on a high volume of grants and investment rounds while having to sell a high-risk project and maintaining positive public opinion of the project.

The following are three options for a public/private collaboration pathway: 1) A company that starts privately for the development of the project until its Intellectual Property (IP) is purchased by a public entity; 2) a publicly-owned project delegates construction authority to a private entity in exchange for operations privileges during a certain amount of time, such public/private concession modes are common in road development; 3) A public entity could subsidize development of a Space Elevator with blended finance to mobilize private equity and traditional financing. This process is distinct because ownership of the project would remain in the private sector despite the support from public sources. Lastly, another plausible pathway would be the creation of a Space Elevator as an Internal development project for some bigger purpose. If a company or organization needs to send a large mass of material to Space then the development of a Space Elevator could be funded as an investment to reduce the logistic costs of their existing operations, based on its cost-savings potential over rocket alternatives.

Regardless of the pathway chosen, unique megaprojects benefit greatly from the support of a luminary [35] that leads the vision, inspires all the stakeholders, and keeps leading the project with any resource required to keep moving the project forward, despite all the uncertainties. As an example, in 2007, Raitt and Bradley wrote the paper "The Space Elevator: Economics and Applications" [7]. In it, they covered seven megaprojects comparable to Space Elevators, and only two of them have been completed in the last 17 years, the "The Burj Khalifa tower" and the "Palm Islands", both in Dubai. This was thanks to dedicated investors who championed these projects and supported them, despite any financial or technical challenges. Furthermore, these investors were motivated to make these bold investments to create landmarks and to advertise and place Dubai on the World Map as the premium touristic location. Space has already proven to be a prime location for high-profile advertisements, including the record Jump from a balloon by Red Bull in 2012, the Roadster launched by SpaceX Heavy in 2018, or the recent commercial trip to the border of Space by Sir Richard Branson in 2021. These types of moon-shot investors might

be also an opportunity for the development and construction of the first Space Elevator as a wonder of the modern world.

5.7. Applying the investment proposition to other models

This paper focuses on the most common technical solution for the modern Space Elevator, which is a traction-type elevator with a continuous 100,000 km long tether, an Earth port, GEO port, and Apex Anchor. The inequality used throughout this paper is used to evaluate the viability of a Space Elevator, but it is equally applicable to any other technical proposals for alternative space access systems. This section briefly discusses some of those alternatives, because even if the tether material proves to be an insurmountable challenge, the following options could similarly be explored within the same inequality. All of them tap into the immense opportunities for space development and fit the standard characteristics of infrastructure: Immobility (fixed in space for specific geography); Longevity; Expensive & Public service [73]. They also share the same two entry barriers, a high initial capital expenditure, due to their infrastructure nature, and the necessity to prove part of their technology at scale.

The underlined multi-stage Space Elevator is a variant of a Space Elevator that utilizes kinetic concepts from a Launch Loop system. This Space Elevator has a continuous tether that covers the circa 100,000 km length from Earth to Apex anchor. The multi-stage system has one or several tethers, and each of them covers just a part of that length and connects to the next one with an ambit. The original concept was introduced by John Knapman with his Stage One in 2011 [74]. The lowest stage would be an enclosed tube, covering up to the first 100 km, which is the harshest environment section due to winds, oxygen, and tether tension. The second stage would continue in the vacuum of space up to 6000 km. The Space Elevator tether would connect with the ambit, located at the top of the stage, and continue through GEO and out to the Apex anchor. In 2019, the design was updated extending the system design for up to five stages [75]. While every extra stage increases the system complexity, it also reduces the maximum tensile strength required for the tether. In the case of the five stages design, the strength required could be covered with materials commercially available today. On the other hand, this system requires high maintenance energy to keep the vacuum in the tube and to keep the bolts traveling via electromagnetic levitation with active magnets. Active structure technology, understood as moving elements that hold kinetic energy to increase the strength of a structure, has not been proven by any industry, not even at small scale in a lab. The specific solution required for this system, with high-speed bolts traveling for 100 km, and its maintenance and energy demands, would need to be evaluated after it, with different scale models. This is the ongoing plan by John Knapman and his partners.

The underlined Slingatron is a spiral railway that turns in non-concentric circles in a way that accelerates the payload with centrifugal forces until it gets released at a very high speed (<10 m/s) at the end of the railway [76]. The concept was presented by Tidman et al., in 1995, and it was developed further during that decade. The biggest challenge of the system is the friction that the payload would have, first with the circular railroad and then with the atmosphere before it reaches orbit. The most common solution for rail friction would be magnetic levitation, which is still a technology to be proven on this very high-speed application. There are no perfect solutions for the air drag and air control, except the aerodynamic design of the payload container and the need to have a second stage rocket as a way to steer the payload direction during the atmosphere uncertainties. While this method has air drag losses, they seem to be much less than the ones for chemical rockets. Another limitation of the system is the huge G-forces that the payload suffers during acceleration. This makes it not viable for humans or sensitive equipment, but it could still be used to send bulk payloads such as water. There was a Kickstarter campaign in 2013 led by Dr. Witherspoon's corporation, one of the co-authors of the first underlined Slingatron publications [76,77], but it didn't reach the required initial funding. The

California-based Start-Up "Spin Launch" [78], founded in 2015, has been working on an updated design and they keep increasing their efforts toward that goal.

The underlined Launch Loop system, modeled in 1985 by Keith H. Lofstrom [79], is the first 2D megastructure on this list. It uses the same principle of active structures that were already covered with the multi-stage Space Elevator. The bolts traveling inside a tube are called rotors in Lofstrom's concept and the project has similar vacuum needs. The payload is built inside reusable or expendable vehicles, with small rockets for repositioning, with a 10-m-long magnet rack that holds the vehicle off the rotor and accelerates it at 3Gs using eddy current repulsion. The most important modules are Deflector's ambits to turn back and maintain the iron blocks inside the vacuum tube that form the rotor; Stations at 80 km high with an elevator to raise the load from the ground, and with the access point for vehicles to be launched; and the Launch track of 2000 km long to accelerate and release the vehicles and their payloads. The most important technical challenges of the project are the safety design and its protocols, as the structure needs a power supply to keep the rotor moving at a very high speed to hold itself in place, so any accident would release a high amount of energy and put at risk the stability of the structure. Also, a structure of this size, even when located in international waters, would require social and legal support to be built. After interviews with Mr. Lofstrom and other key people related to the project, the research for this paper did not find any working prototype at scale, or any enterprise to pursue its construction.

The *Orbital ring* concept and calculations were covered by Paul Birch during 1982–1983 [80–82]. The basic design consists of a metallic ring spinning over a celestial body that stays in its position thanks to its accumulated kinetic energy, with small correction forces applied via the cables that connect it to the ground, called Jacob's ladders. This system could be built around the Earth using standard abundant materials. The most commonly used material would be slag. However, to build a basic design with two counter-rotating rings, the weight of the required material would be 1.8×10^{11} kg. This is a lot of mass rotating at very high speed in Low Earth Orbit (LEO), which might face some social and legal challenges. The hurdle for construction of this project in the colossal initial mass requirements to launch to LEO, while this is still true, the recent decrease of launch cost per Kilogram - thanks to the development of reusable rockets – would make this project plausible on paper from an economic perspective. The construction method would require the launch of 1.8×10^8 kg of material for an initial lightweight orbital ring with 20 Jacob's ladders, which could lift the rest of the required material for a full orbital ring in less than a year. To put it in perspective, the total weight of the International Space Station (ISS) weight is 4.5×10^5 kg, so the initial material would be equivalent to four hundred ISS's, which is large but technically plausible.

The underlined StarTram concept was first published in 2001 by James R. Powell and others [73,74,83]. The development was based on the superconducting magnetic levitation (Maglev) that Dr. Powell co-invented together with Gordon Danby, which led to the development of magnetic levitation trains [84]. The StarTram was also based on the MagLifter design from 1994, by NASA's engineer Dr. John Mankins [85]. The StarTram design consists of a vacuum tube that will carry the vehicle with the payload with an entry at ground level and an exit high enough that will create enough speed and delta-V for the loads to leave the planet. The exit of the tube will have a plasma window that keeps the tube in vacuum conditions that will deactivate for a moment when the vehicles leave the tube. The design has the first generation with a tube of circa 130 km that goes from sea level to the peak of a mountain at 6000 m high. The unmanned vehicles will be accelerated at 30 g and leave the StarTram with a speed of 8.78 km/s, with an angle of 10°. The second generation consists of a tube of circa 1000 km with an acceleration of 2–3 G's and would be rated for humans. A segment of the tube is not elevated, most likely in a tunnel, and the other segment goes up to an exit altitude of 20 km. The tube is held in place via magnetic levitation from a huge current of 280 mega-Amps on the ground and fourteen

mega-Amps in the tube that cause a repulsion compensated with tensile cables that stabilize the structure. It has been stated that Generation 1 construction timeline would be 10 years from funding, and Generation 2 in another 10 years. Currently, Powell and Danby are aiming to get the necessary resources to start the project.

6. Conclusion

The value of a Space Elevator will not be realized in the sale of tickets to space, but in the enabling environment, it will create for the space economy. Space Elevators are not like rockets. Rockets are a service. A Space Elevator is a trellis for growing an economy in space, and the last port of call for accessing the entire solar system. If constructed, it will give unprecedented access to the tremendous value of space.

With the development of new materials that have the viability to provide a tether, the dream of a Space Elevator is primed to become a reality, but only if it can receive the immense funding necessary. Focusing on only the cost to build a Space Elevator (in material and labor or the relative value it provides in shipping cargo to space) will not entice the necessary funding. Cost per kilogram is a consumer perspective and not an investment argument. A Space Elevator is an infrastructure construct, not an enterprise service. Therefore, it provides maximum value when there is maximum utilization, which takes place when the price for consumers is minimized, and its cost is subsidized with increased economic productivity. Therefore, any conversation based on the value of a Space Elevator as a revenue-generating system that provides the same service as rockets at a lower price misunderstands the true value proposition of the endeavor.

The Space Elevator community needs to persuade investors with the foresight and capital to build it. The inequality presented in this paper (2) is fundamental to the creation of an investment proposition necessary for funding such a large-scale endeavor. Value needs to be presented like that of the Transcontinental Railroad, in its ability to create global economy-wide growth, innovation, and trade. On the other side of the equation, the biggest hurdle for securing funding for the development of a Space Elevator is working to reduce both the perceived and actual risk in all four total-failure categories: political, social, market, and technical. To achieve this risk reduction, we need to engage national and international groups, develop institutions and social movements around its success, validate the engineering viability of the laboratory-proven materials, and foster a stable and productive space market with the resiliency to weather the many years necessary for the construction of a Space Elevator.

The first-time humanity landed on the moon was an iconic moment in history. With a Space Elevator, we can make space so accessible that anyone can get to space and travel anywhere in the solar system or even to other stars.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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