Electromagnetic Space Launch Infrastructure – A Techno-Economic Analysis

(Full-Length Paper)

Philip Swan
The Atlantis Project
Redmond, WA, USA
philswan@project-atlantis.com

***Abstract*— Space access infrastructure can now outperform rockets on levelized cost per kilogram. The architecture with the lowest technology adaptation degree of difficulty in the field of electromagnetics is shown to be the Tethered Ring. A Tethered Ring is a dynamic structure that can be built on Earth and raised into the stratosphere without a pre-existing space infrastructure, a space-based industry, or any need for expensive rocket launch services. It can support facilities (for example, launch systems, transit systems, communications gear, and habitable spaces) at an altitude of 32km and at an estimated capital cost of under $110 per kg supported.**

Keywords—space, launch, infrastructure, electromagnetic, levitation, linear motor, magnetic bearing

I. INTRODUCTION

The difference between a payload on the surface of the earth and a payload in orbit, or on its way to a destination such as Mars, can be characterized by the payload's change in gravitational potential energy and velocity. Chemical rockets are conventionally accepted as a preferred way to impart these changes. Rockets are subject to the Tsiolkovsky Rocket Equation, which is generally used to explain the physics of why rockets launched from earth to orbit must be very large in relation to their payloads.

Proponents of non-rocket technologies propose ways to launch payloads into space where much of the speed and altitude needed to achieve orbit is provided by a propulsion technique that is not subject to the limits of the rocket equation. There are many such proposals, so it can be challenging to understand which of them, if any, are currently technically and economically feasible.

To be technically feasible, every aspect of the non-rocket technology's architecture must be based on a well-established heritage technology. The "adaptation degree of difficulty" from the form used in the heritage technology to the form used by the non-rocket launch technology should be low. To be economically viable, it must be possible to estimate, with reasonable accuracy, the cost to design, test, build, and operate the non-rocket technology. There needs to be a credible plan that explains to an investor how the implemented technology will service the debt that will be incurred to build it.

The socio-economic benefits of fully maturing a non-rocket technology and putting it into service can be determined by identifying which non-rocket technology is the most promising and comparing it to the best available rocket technology. This should be done based on a defined set of anticipated near-future circumstances. The rocket technology used in our comparison is Starship, a fully reusable heavy-lift rocket architecture being developed by SpaceX. The non-rocket technology used is the tethered ring, which is a structure that can support an electromagnetic mass driver in the stratosphere which in turn will be used to launch hypersonic vehicles into space.

II. CIRCUMSTANCES FOR THE COMPARISON

Rockets are a well-established technology because of past circumstances. For example, cold-war geopolitical conflict strongly encouraged the rapid maturation of single-use chemical rockets optimized for delivering small payloads between two points on Earth. New circumstances favor sustainable launch systems capable of delivering heavy payloads to far-away destinations such as The Moon and Mars.

For the purposes of our relative socio-economic benefit analysis, we will assume that humanity's space colonization ambitions include the creation and continual supply of an industrial base on the Moon and a self-sustaining human colony on Mars. We will also assume that earth's economy has transitioned to being fully carbon-neutral, and that any operations that cause emissions must also bear the cost of offsetting those emissions.

We will assume, based on various reference missions described in the literature, that 500,000 tons of payload mass (not including the delivery vehicles) transported from the Earth to the surface of the Moon, and 1,000,000 tons of payload mass delivered from Earth to the surface of Mars, over a period of 50 years, will be enough to meet the initial goals of humanity's solar system colonization programs.

III. SELECTION OF ROCKET TECHNOLOGY

In making this selection we considered whether the system is able to accomplish our proposed mission and whether there is a source of hard data that we can use to accurately estimate the system's costs and capabilities.

There is excellent data on rocket technology costs from NASA. Rocket launch costs estimates were obtained for NASA's commercial resupply services and commercial crew programs to the International Space Station (ISS). Payments made to service providers (see Figure 1) are made available on usaspending.gov[1][2][3][4] and detailed payload data (see Figure 2) is available for almost all missions to the ISS.

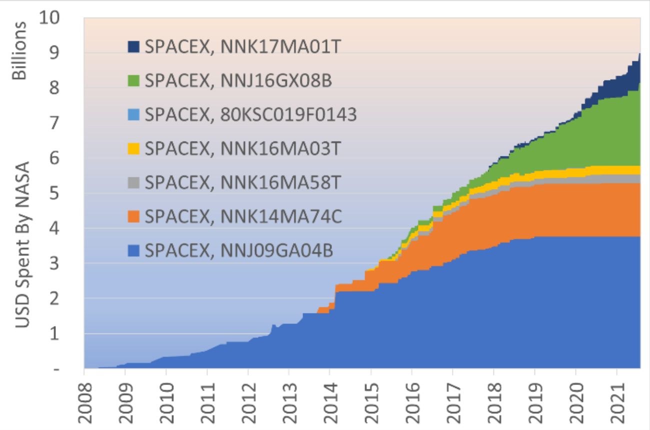

Figure 1: Spending on SpaceX ISS resupply contracts

ICEAA-IEEE APWC 2022, Cape Town, South Africa, September 5-9, 2022

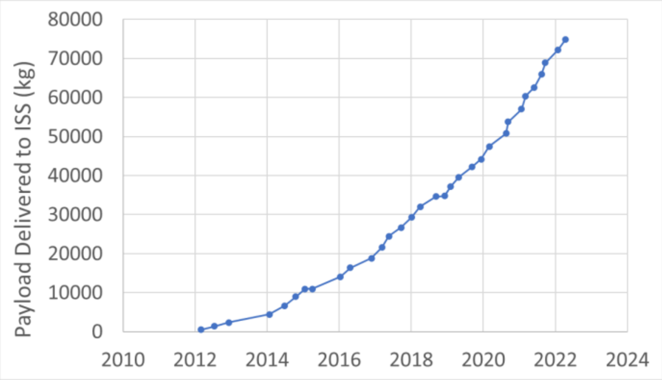

Figure 2: Mass delivered to ISS by SpaceX

By combining Figure 1 and Figure 2, we can graphically represent the relationship between mass delivered and money spent.

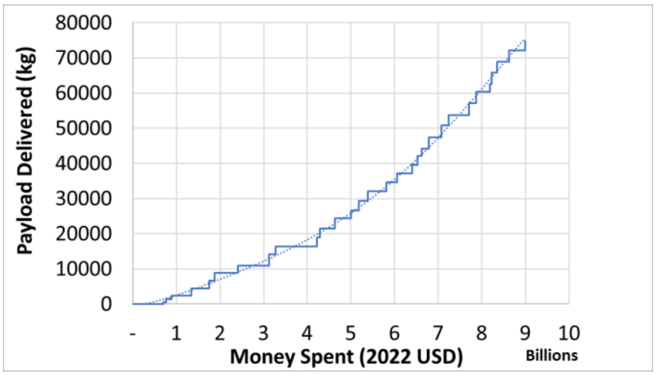

Figure 3: Payload to ISS versus NASA payments to SpaceX

The inverse slope of Figure 3 is the cost per kg, which is plotted below.

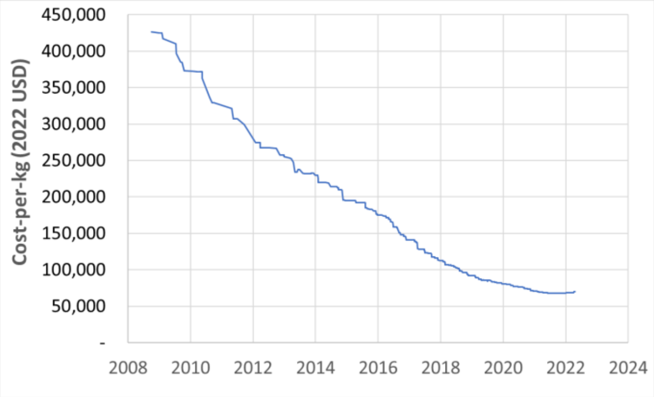

Figure 4: Cost of ISS resupply services versus time with Falcon9

From Figure 4, the cost of commercial resupply services has, as of 2022, has reached $68,000 USD/kg. These results agree with data in Table 3 of a 2018 Office of Inspector General report, which projected a cost per kg of 71,800 USD/kg.[5]

While the data shows that NASA is paying high costs for ISS resupply, it should be noted that SpaceX's ride share fees are currently lower. For example, it costs 1.1M to place 200kg into sun-synchronous orbit, or $5500 USD/kg.

Through its CCtCap funding, NASA pays for Falcon9 plus Crew Dragon launches to the International Space Station; however, Starship is SpaceX's next generation system, and SpaceX optimized it for travel to Mars. A cost estimate for the Starship launch system can be arrived at by comparing the two systems on a component-by-component basis and applying adjustment factors[1]. In Table 1, the "Factor" column captures how the change to a component's technology will impact cost. The "Weight" column captures the relative importance of the component to the cost of the overall system.

TABLE I. ADJUSTMENT FACTORS AND WEIGHTINGS

Component	***Falcon9 Description***	***Starship Description***	***Factor***	***Weight***
Propellant	RP1/LOX	Methyl/LOX	1	0.02
First Stage	Reusable	Reusable	1	0.3
1st Stage Return Location	Drone Ship	Launch Site	1.1	0.2
Second Stage	Expendable	Reusable	0.25	0.05
Landing System	Deployable Legs	Tower Catch	0.5	0.01
Primary Material	Aluminum	Stainless Steel	1.2	0.05
Thermal Protection	None	50% of 2nd stage	1.1	0.04
Engines	Merlin 1D	Raptor2		
Engine Thrust	854/981 kN	2255 kN	1	0.01
Engine Mass	470/520 kg	1600/1760 kg	1	0.05
Exhaust Velocity	3000/3414 m/s	3208/3433 m/s	1	0.17
Payload Ratio	0.0297	0.030	1.01	0.01
Weighted Sum			0.9925	1.0

After weighting and tallying the adjustment factors for Starship, it becomes apparent that from a performance perspective, the technology changes made between Falcon9 and Starship are not likely to be transformative, and thus will not have a significant direct impact on rocket-based space launch costs – at least not in the way that one would expect from, for example, a new form of advanced propulsion or a scientific breakthrough in fuel chemistry. Starship and Falcon9 are both equally and fundamentally limited by the rocket equation, the chemical properties of known rocket fuels, and the maximum stresses that affordable and workable aerospace-grade materials can tolerate. Rather, the system appears to be designed to achieve higher throughput.

Some costs, such as fuel, oxidizer, and certain regular maintenance and refurbishment costs are proportional to the rate that mass is placed into orbit. On a per-kg basis, these costs will only improve a small amount as the amount of mass launched increases. Innovations could bring refurbishment costs down, but the need to maintain Starship's large thermal protection system could easily negate those gains. It is too early to predict with any certainty which way the overall refurbishment costs will go.

Another proportional cost that might increase in the future (from zero) is the cost of emissions. Table 1 lists the assumptions that were used to estimate that 110 kg of CO2 will be emitted per kg of CO2 delivered to LEO by Starship. If the public pressures launch providers to purchase carbon credits to offset their emissions, this will increase per kg costs.

Table 1: Calculation of CO2 emissions per kg launched.

Variable	**Value**	**Units**
Starship Payload to LEO	100,000	kg
Superheavy Oxygen Mass	3,600,000	kg
Superheavy Methane Mass	800,000	kg
Starship Oxygen Mass	981,818	kg
Starship Methane Mass	218,182	kg
CO2 to Methane Mass Ratio	2.75	
CO2 emitted per launch to LEO	2,800,000	kg

---

[1] The use of weighted adjustment factors should be conceptualized as a though exercise, not a bold declaration of objectivity.

CO2 emitted per kg to LEO	28	kg
Electricity per kg of O2	3,600	Wh
US Grid Carbon Intensity	500	kg/MWh
Carbon emitted to produce O2	8,247,273	kg
Total CO2 per launch to LEO	11,047,273	kg
CO2 emitted per kg to LEO	110	kg

If humanity’s space ambitions create a significantly larger market for launch services, then one-time costs and the yearly operating costs may be amortized over a larger amount of mass launched. The challenge here is that the baseline system (Falcon9 plus Crew Dragon) already has an impressive performance record. It has achieved high reusability counts, the first stage can return to the launch site or a drone ship, 90% of the system’s engines are reused (96% for the Falcon Heavy variant), and the system is already launching at a rate of roughly once per week. So many of the proposed techniques for further reducing costs are already, at least partially, “baked-into" to the empirically derived cost-per-kg of our baseline system.

The degree to which NASA and the taxpayers can expect to see the real-world cost of space launch improve over time, relative to the empirically derived cost of our baseline system, is certainly a debatable question. It is also one deserving of careful, diligent, and meticulous analysis by professionals who work for, and represent, the interests of the taxpayers and other major users of space launch systems. For the remainder of this paper, it will be assumed that current costs remain where they are. The reader is encouraged to make any adjustments to the analysis that they feel are appropriate by using new data as it becomes available over time.

IV. SELECTION OF NON-ROCKET TECHNOLOGY

Non-rocket technologies considered for pre-selection met the following criteria:

#	***Pre-selection Criteria Description***
1	Buildable entirely with currently mass-produced industrial materials
2	Supports a human-rated launch capability
3	Sensitive cargos (such as people) on their way to the Moon or Mars, cannot be made to linger within the Van-Allen belts, or the need for adequate radiation shielding is factored into cost and performance estimates for the technology
4	If the technology’s structural elements are exposed to space debris, a sound long-term strategy for surviving high-speed impacts is required. Otherwise, the risk of a Kessler Syndrome event occurring within the 50-year operational lifetime will deter investment

Technologies that did not meet the pre-selection criteria include space elevators, space elevator hybrids, skyhooks, rotovators, space guns, slingatrons, orbital rings, and the string transportation system.

Non-rocket technologies that meet the pre-selection criteria include an electromagnetic launcher supported by several space fountains or space towers (herein: space fountains), launch loops, the tethered ring, and StarTram.

Of these, StarTram was not selected because it projects powerful magnetic fields into the environment, and because there is insufficient information in the literature that states convincingly that the environmental impact of such fields would be benign.

The remaining technologies all use active support, which means that, unlike traditional static engineering structures such as the typical bridge or building, they rely on the constant motion of at least one component to remain stable. For example, a skyscraper with a tuned mass damper is a structure that employs active support to provide its tenants with stable high-altitude floorspace. Airplanes also support reasonably stable floorspace at great heights by using active support. The pre-selected non-rocket technologies all employ some form of fast moving electromagnetically supported mass-stream for active support.

Relevant heritage technologies for fast moving electromagnetically supported mass-streams include active magnetic bearings, linear motors, and magnetically levitated trains. While non-rocket technologies that employ active support show enormous potential to be transformative, there is relatively little published material that assesses the degree of difficulty of adapting these heritage technologies to meet the requirements of actively supported structures.

A set of five possible mass stream requirements were considered. If the non-rocket technology’s architecture imposes one or more of the requirements, it is likely that the difficulty of adapting the available heritage technologies to the needs of the active structure will increase.

#	***Potential Mass Stream Requirements***
1	There is an ongoing operational requirement for efficient energy transfer to accelerate and decelerate the speed of the mass stream (as opposed to just diverting it) on a frequent periodic basis, such as every time it completes a circuit of its levitation system’s track
2	The specified mass stream uses discrete pellets or bolts versus a continuous ribbon of material
3	The mass stream uses expansion joints as opposed to being as uniform as possible in its direction of travel
4	The mass stream experiences significant changes in lateral acceleration during its circuit (for example, a hairpin turn) as opposed to experiencing relatively consistent lateral acceleration
5	After being placed into service, a portion of the mass stream system is at risk of damage due to a catastrophic event, such as an earthquake, volcano, or terrorist attack involving, for example, an unsophisticated torpedo or commandeered aircraft

The above considerations were mapped to the short-list of non-rocket technologies as follows…

Technology	***Consideration Applies?***				
	1	***2***	***3***	***4***	***5***
Space Fountains	Yes	Yes	No	Yes	Yes
Launch Loop	No	No	Yes	Yes	Yes
Tethered Ring	No	No	No	No	No

Based on these considerations, the Tethered Ring was found to have the lowest technology adaptation degree of difficulty of all the technologies.

V. DETAILED DESCRIPTION OF THE TETHERED RING

The tethered ring is a dynamic structure comprising three main components: at least one stationary ring, at least one moving ring per stationary ring, and many tethers.

A stationary ring is an evacuated tube that is formed into a circle of a fixed diameter that is generally specified to be somewhere between 50% and 95% of the diameter of the planetary body that it is built to operate on.

Within a stationary ring there is a magnetic levitation system that supports at least one moving ring. An unconstrained moving ring would normally stretch and expand, but in this case it does not because it is fully supported by the magnetic levitation system. Its inertial forces are thus transferred to the stationary ring.

The stationary ring also does not expand because it is prevented from doing so by the combined forces of the

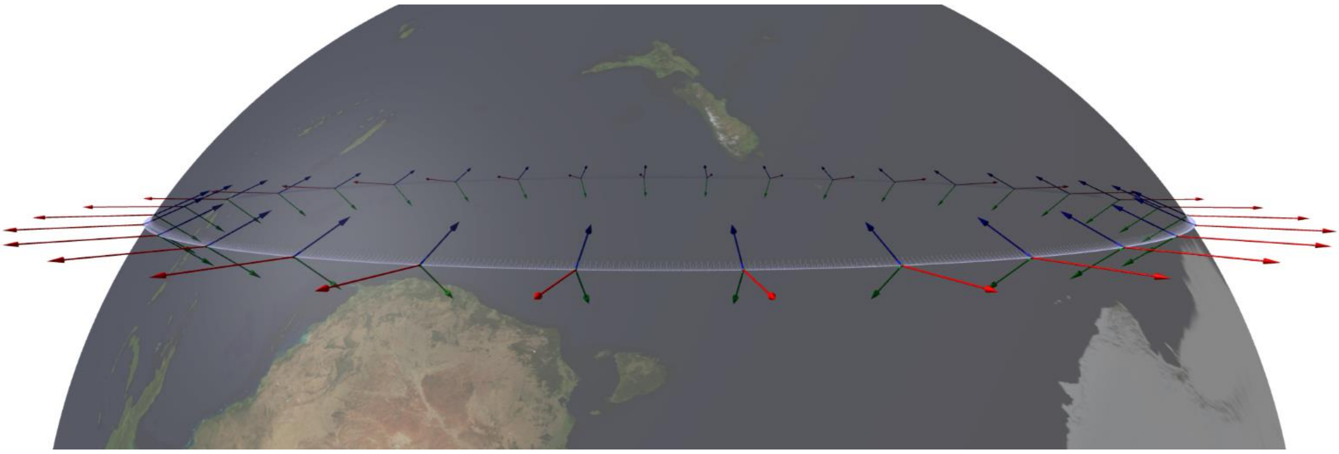

Figure 5: Ring self-supported at an altitude of 32km. Inertial forces (red) plus tensile forces (blue) offset the pull of gravity (green).

planet's gravity and the tensile forces applied to it by the tethers (see Figure 3).

The tethered ring can be constructed on earth and then raised to altitude by the act of tensioning its tethers.

Tethers are assumed to be constructed from carbon fiber tow. An engineering factor of 2 is assumed in the calculation of how much carbon fiber is needed. Tether anchor platforms include systems that dynamically tension the tethers and periodically cycle individual strands out for inspection or replacement. The tether cross section is tapered to achieve constant tensile stress along its length. The curvature of the tether is defined by the equation for a catenary of constant stress.

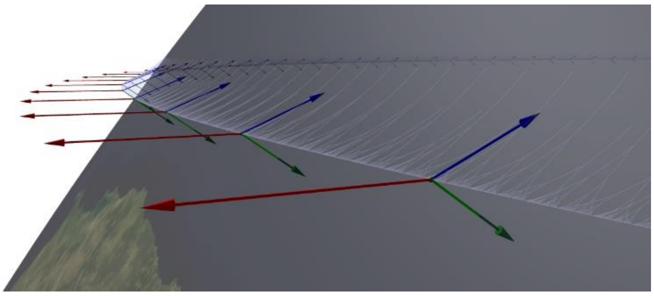

Figure 6: Zoomed in view shows forking and overlapping tethers.

The moving ring is magnetically coupled to the stationary ring by a magnetic levitation system. The permanent magnet biased active magnetic bearing[6] is an example of a heritage technology for such a system, except that the levitated shaft (that is, the moving ring) moves through the bearing longitudinally as opposed to rotating on its axis within the bearing. It is, in essence, a long active magnetic linear bearing formed into a loop. The system is engineered so that magnetic fields are homopolar in the axial direction (that is, the direction of motion of the moving ring) and heteropolar in the radial direction. This minimizes operational costs and heat generation because the longitudinally travelling moving ring will experience steady magnetic fields, and steady fields do not induce currents within conductive components. Use of laminates and non-conductive materials, such as ferrites, where appropriate, also helps to prevent the generation of induced currents. Minimization of induced currents leads to

- Less drag on the moving ring,
- Lower energy requirements for maintaining the ring's rotational speed,
- Less waste heat generation, and
- Reduced thermal dissipation requirements.

Magnetic Resonance Imaging (MRI) is a heritage technology because the moving ring's low-friction magnetic levitation depends on a magnetic field homogeneity on the order of a few parts per million (ppm) over a certain diameter of spherical volume. As with MRI machines, the tethered ring will achieve high homogeneity by placing metal shims in appropriate locations and by tuning the electrical currents within shim coils.

While the steady, homogeneous, magnetic fields will produce the forces needed to curve the path of the moving ring, Earnshaw's theorem explains that the fields generated by permanent magnets alone are insufficient for stable levitation. Within the active magnetic bearing industry, positional sensors, electromagnets, and control circuits are added to achieve stable levitation. These active components consume energy primarily when the system is perturbed by external disturbances. Mechanically isolating the stationary ring from disturbances can help to reduce the amount of energy used by the active components.

The space within the stationary ring that the moving ring travels through is evacuated by using turbo molecular pumps to reduce air friction, the associated generation of waste heat, and to minimize wear due to sputtering. The ambient atmospheric pressure at the ring's operational altitude is low, making it easier to maintain the vacuum.

VI. ECONOMICS

This section covers how we estimate the cost of building a tethered ring and how business models that make use of the tethered ring can help to recoup its capital and operating costs.

A. *Cost Estimate*

In support of the cost estimate, the author has written a JavaScript version of the tethered ring's architectural model and has made it freely available on the Internet[7]. At present, the model supports roughly 150 adjustable input parameters that allow the user to customize the tethered ring in numerous ways. It will then calculate and output 231 design parameters. Included among these is estimated cost data. For example, the current default settings define a ring located at an altitude of 32 km with a circumference of 32,800km. The model estimates the cost for this variant to be 47 billion US dollars.

Note: Debugging tools built into the most widely supported browsers can set breakpoints, watch variables, and walk the model's code. The model is also available on Github[8].

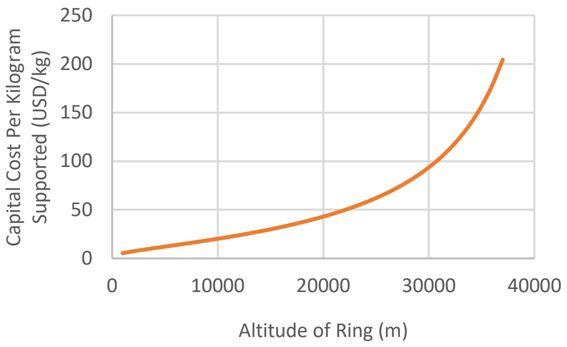

Figure 7: Capital Cost per Kilogram of Load Supported

One of the critical performance metrics of the architecture is the capital cost per kg of load supported (see Figure 7). This metric should not be confused with the electromagnetic launch to Low-Earth Orbit (LEO) energy costs, which could be on the order of $2 per kg, assuming a launch system energy conversion efficiency of 50%.

B. *Electromagnetic Launch System*

The tethered ring supports an electromagnetic launch system at its design altitude. Passengers (and cargo) can travel up to the launcher within elevator cars. From there they board a space vehicle which is accelerated down an evacuated launch tube.

The vehicle exits the tube through an airlock with fast-acting doors and travels through the residual atmosphere to space. To provide a smoother ride, a rocket engine fires briefly as the vehicle exits the tube to prevent vehicle deceleration due to friction with the rarified atmosphere. Rocket propellants are also circulated through the nose cone to assist with thermal management.

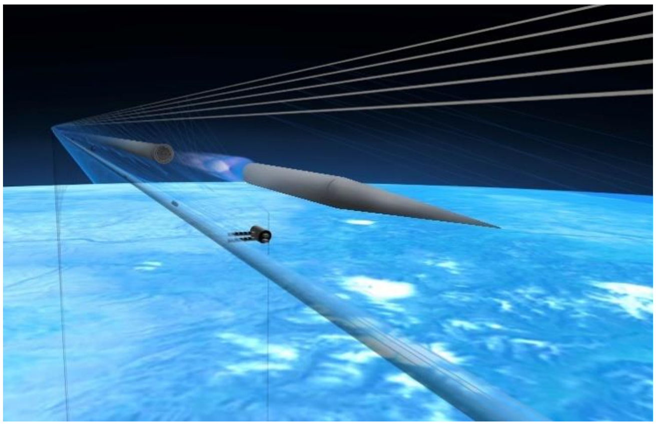

Figure 8: Launch tube with a space vehicle exiting at high speed.

Most non-rocket technologies to date have focused solely on providing low-cost launch services. The tethered ring is designed to be a multi-use infrastructure with multiple additional business models and revenue streams. Some of these include high-speed carbon-neutral international travel, solar power generation, transmission, and storage, communications services, and high-altitude real-estate.

C. *High-Speed Carbon-Neutral International Travel*

Presently, most international travel is provided by sub-sonic commercial aircraft which are incompatible with the world’s desire to transition to a carbon neutral economy by 2050. Batteries are not energy dense enough to electrify the kinds of planes that fly the long-haul routes. Traditional types of rail corridors (that is, on-grade, below-grade and above-grade) for high-speed electric trains are costly due to either land acquisition and permitting costs, tunnelling costs, or viaduct costs.

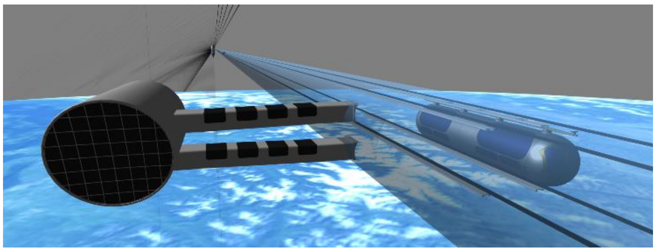

Figure 9: Ring-mounted evacuated tube transit system.

A ring mounted evacuated tube transit system is a sustainable solution and a disruptive technology. It is faster, quieter, more convenient, and less costly to operate than airliners. Individual vehicles are small, like business jets. They depart frequently, are autonomous, and travel very fast. They travel on maglev tracks, and are not burdened with heavy components such as wings, engines, fuel tanks, and landing gear. They can’t be hi-jacked so security screening can resemble train-station security rather than airport security. Ring-mounted transit has low per-kilometer costs because, like planes, the transit corridor is in the stratosphere. This avoids the expense of acquiring and permitting land.

D. *Solar Power Generation*

Mounting photovoltaic (PV) solar panels on the ring for the purpose of sustainably generating marketable electric power has several advantages when compared to terrestrial PV solar. Ring-mounted panels will be more efficient since they are above the clouds, above 90% of the atmosphere, and because they will tend to stay clean. With tracking, they will generate at close to full power from sunrise to sunset. At the ambient temperature at 32km altitude of -40˚, the panels will be more efficient and will last longer. They can be made lighter and at lower cost as they will not need to be hardened to withstand hailstorms.

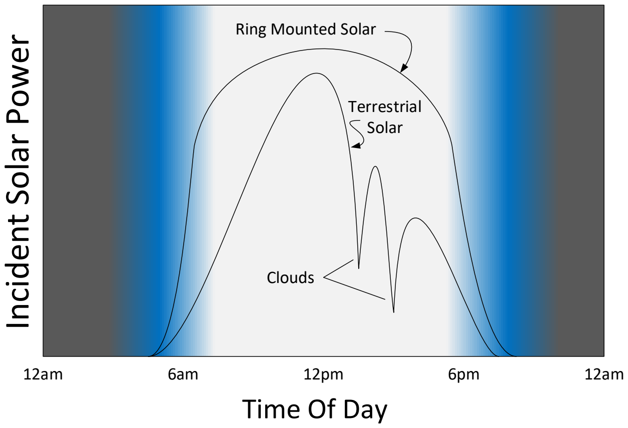

Figure 10: Incident solar power versus time of day.

E. *Power Storage and Transmission*

The moving rings in the tethered ring reference design store 58 TWh of kinetic energy. Theoretically, power can be added to the ring in one place and taken out in another. So, the moving rings can both store energy and transport it. Wires can transfer power from the ring to the ground.

Allocating 0.5% of the stored kinetic energy to time-shift intermittently generated solar energy would be equivalent to manufacturing $635 billion of Li-Ion based grid-scale storage. To illustrate, let E_T be the total energy time shifted.

$$StorageCapacity = Total\ Storage * 0.5\%$$

$$E_T = StorageCapacity \cdot ServiceLife \cdot CyclesPerYear$$

$$= 58\,TWh \cdot 0.005 \cdot 50\,years \cdot 365 = \ 5292\,TWh$$

Let C be the cost of time-shifting energy with Li-Ion battery storage and let DoD be the depth of discharge.

$$C = \frac{Li\text{-}Ion\ Cost}{DoD \cdot CycleLife} = \frac{217\frac{USD}{kWh}}{0.8 \cdot 2200} = 0.12\frac{USD}{kWh}$$

Let V be the value of the storage capacity.

$$V = 5292\,TWh \cdot 0.12\frac{USD}{kWh} = \boldsymbol{635B\ USD}$$

F. *Communications Services*

Recently there has been commercial interest in providing internet service by using LEO satellite mega-constellations. In these systems customer equipment connects to a satellite which then connects to a ground station which is, in turn, connected to the Internet.

Because the satellites are in constant motion, the customer's equipment needs to have a clear view of the sky. This equipment also needs to locate and track each satellite as it passes overhead, adding to its cost and complexity.

A LEO satellite uses propellant to maintain its orbit and it uses batteries to provide power while in the Earth's shadow. Since batteries wear out and the propellant supply is limited, satellites need to be replaced periodically.

By mounting communications gear on tethered rings, a more profitable service can be created. Recurring satellite launch costs are avoided. Ring-mounted gear would have a fiber connection to the internet, so there is no need for ground stations to handle back-haul. Customer equipment no longer needs a clear view of the entire sky. Instead, it only needs line-of-site to a transceiver mounted on the ring. User equipment is cheaper because it does not need to track moving targets.

Because ring-mounted gear is 17 times closer to the customers, it can place 17 squared, or roughly 300 times, as many beams on the ground per square kilometer. This means 300 times as many customers can be served in a region before the system's bandwidth is saturated.

Finally, ring-mounted communications gear will not exacerbate the space debris problem, and it will not photo-bomb any astronomical observations.

G. *Real-Estate*

A tethered ring can support habitable floorspace which can be sold or leased to generate revenue. Pre-construction sale of real-estate is a potential source of early funding.

Figure 11: Tourist viewing the Earth from a high- altitude.

H. *Economics Summary*

Further research into the theoretical and practical efficiency limits for electrical to kinetic energy transfer to and from a high-speed moving ring would be invaluable. Such research will help to improve the accuracy of calculations that support the business models. If reasonably efficient energy transfer is achievable, then, for example, the solar power generation, storage, and transmission business model could deliver on fusion's promise to one day provide limitless clean baseload power while using techniques that are less complex than those currently being investigated by the high-energy fusion research community.

VII. ROCKET VERSUS NON-ROCKET TECHNOLOGY

A. *Launch Costs for Colonization by Using Rockets*

Recent technical advancements in rocketry have made over 90% of the rocket reusable (that is, the first stage, fairings, and capsule). Despite this, data clearly shows that from a major customer's perspective the cost of space launch remains high. Current launch rates are already frequent enough for many of the expected benefits associated with large economies of scale to be accounted for in data published by NASA and the US government.

The destination for resupply trips to the ISS is LEO. Trips to the Moon and Mars with Starship will require refilling in LEO. We have chosen to use a refilling factor of 6 for the analysis. In other words, we are assuming that the cost of delivering 100 tons to the Moon or Mars will be the same as delivering 600 tons to LEO.

The cost of placing 0.5 megatons on the Moon and 1.0 megatons on Mars is thus…

$$Cost = (1 + 0.5) \times 10^9 \times 6 \times PricePerKgToLEO$$

$$Cost = 1.5 \times 10^9 \times 6 \times 67{,}490 = 607\ Trillion\ USD$$

B. *Launch Costs for Colonization by Using Tethered Ring*

A tethered ring mounted electromagnetic launcher is transformative because the system is not subject to the physical limits inherent in the rocket equation. For launches to the Moon and Mars, we will assume that the launcher has an electrical-to-kinetic energy transfer efficiency of 50%. Further research on the efficiency of electrical to kinetic energy transfer in high-speed linear motors would help to improve the accuracy of our economic analysis. Let us assume a launch speed of 15km/s – somewhat faster than the DeltaV needed to reach Mars from Earth's surface. By launching at this speed, the journey will be shorter, the crew will consume fewer provisions, and they will be exposed to less cosmic radiation.

Let us assume that for each 100 tons of crew and cargo we also need a 100-ton lander. This means that the launched mass will be double the delivered mass. We will assume wholesale electricity costs of 0.05 USD/kWh, or 0.014 USD/Mega-Joule.

$$Cost = Cost_{Electricity} \times \frac{mv^2}{2} \times efficiency$$

$$= 0.014 \frac{USD}{MJ} \times \frac{3.0 Mtons \left(15 \frac{km}{s}\right)^2}{2} \times 0.5$$

$$= 2.36 \; billion \; USD$$

As we mentioned earlier, the materials costs for the tethered ring are estimated by the architectural model to be 47 billion USD; however, this cost is shared by the multiple businesses that the tethered ring will support.

VIII. CONCLUSIONS

Current rocket launch costs continue to remain high based on analysis of recent data from NASA's ISS commercial resupply contracts. The socio-economic benefits of developing space infrastructure in the form of a tethered ring are clearly compelling. Of all the non-rocket space launch proposals in the literature, the tethered ring is the easiest to engineer by adapting existing heritage technologies, such as active magnetic bearings and carbon fiber cables. Our analysis shows that the architecture can, once operational, reduce the launch costs for a hypothetical solar system colonization program by five orders of magnitude, from 607 trillion down to 2.36 billion USD. There are also significant societal benefits associated with the additional business models supported by the tethered ring, such as high-speed carbon-neutral international travel and solar power energy generation, storage, and transmission.

The tethered ring provides sustainable space launch services, terrestrial transportation, base-load power, and communications infrastructure. Given the enormous potential of the technology, its development merits a focused, sustained, and well-funded research effort. The technology is easier to mature than other endeavors, such as nuclear fusion, that already receive billions of dollars of funding every year.

ACKNOWLEDGMENT

The author wishes to thank Alastair Swan and Ceana Prado Nickle for their on-going years of support developing the technology, and of course, for their latest contributions as reviewers of this paper.

IX. REFERENCES

[1] "IDV to SPACE EXPLORATION TECHNOLOGIES CORP. | USAspending." https://www.usaspending.gov/award/CONT_IDV_NNJ09GA04B_8000 (accessed Jul. 16, 2022).

[2] "IDV to ORBITAL SCIENCES CORPORATION | USAspending." https://www.usaspending.gov/award/CONT_IDV_NNJ09GA02B_8000 (accessed Jul. 16, 2022).

[3] "IDV to SIERRA NEVADA CORPORATION | USAspending." https://www.usaspending.gov/award/CONT_IDV_NNJ16GX07B_8000 (accessed Jul. 16, 2022).

[4] "Federal Awards | Keyword Search | USAspending." https://www.usaspending.gov/keyword_search/CCtCAP (accessed Jul. 17, 2022).

[5] Office of Inspector General, "Audit of Commercial Resupply Services to The International Space Station," Apr. 2018, page 21. Available: https://oig.nasa.gov/docs/IG-18-016.pdf

[6] G. Schweitzer and E. H. Maslen, "Magnetic bearings: Theory, design, and application to rotating machinery," *Magnetic Bearings: Theory, Design, and Application to Rotating Machinery*, pp. 1–535, 2009, doi: 10.1007/978-3-642-00497-1/COVER.

[7] P. Swan, "Interactive 3D Simulation of the Tethered Ring." https://www.project-atlantis.com/wp-content/threejs-simulation/TetheredRing/index.html (accessed Jul. 16, 2022).

[8] P. Swan, "Tethered Ring Architectural Model, JavaScript and Three.js Repository on GitHub." https://github.com/philipswan/TetheredRing (accessed Jul. 16, 2022).