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BENEFICIAL ENVIRONMENTAL IMPACTS OF SPACE ELEVATORS

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Abstract

Reliable, routine, safe, and efficient access to space is close at hand. The Space Elevator will be an essential part of a global and interplanetary transportation infrastructure, as it has the ability to improve the Earth's environment. In the community of off-planet movement and with NASA's newest move to put boots on the Moon by 2024, Space Elevators must be a part of the plan. Release from multiple, nearly infinite, locations on the Space Elevator will allow high speed launches to other bodies within and beyond our solar system. The question to be addressed here is: how can the strengths of Space Elevators enable missions of all types, while having little or no negative environmental effects? We believe that not only can it do this, but it can also enable activities in space that will actually improve Earth's environment. This study hopes to show the beneficial environmental effects of building, and daily use, of Space Elevators while showing what kind of missions can be accomplished to improve the Earth's environment. The reality is that as humanity has decided to conduct off-planet activities, there is a tremendous need for logistical support for the movement of goods as well as the transportation of people. With this need, it is recognized that huge numbers of launches will still be going through the atmosphere, contaminating the land around the launch site and the atmosphere along its path, leaving parts of rockets and spacecraft in orbit, and consuming natural resources in large quantities. With this realization comes the responsibility to mitigate environmental impacts while also providing positive environmental benefits from Space Elevator services.

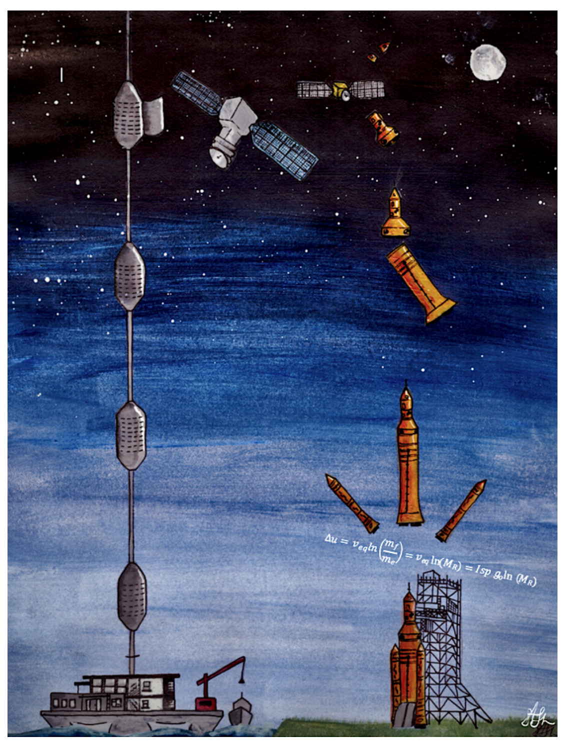

Figure 1, Dual Space Access Architecture (Stanton image)

***1.0 Introduction**:* The Space Elevator will be the transportation story of the 21st century. Reliable, routine, safe, environmentally friendly, inexpensive, and efficient access to space is close at hand. The Space Elevator or Galactic Harbour, will be an essential part of the global and interplanetary transportation infrastructure. With the current efforts to put boots on the Moon and Mars in the next fifteen years, Space Elevators must be a significant component in a Dual Space Access Architecture - Rockets and Space Elevators. In these visions, there will be a tremendous need for logistics support, movement of manufactured goods as well as transporting people. A net assessment study being conducted by ISEC shows that Space Elevators are Big Green Machines designed to improve the Earth's environment through two significant contributions. The first is the remarkable "zero-emission" lift of cargo to space - reducing the environmental impacts of rocket launches. The second is the ability to deploy massive systems to GEO that can actually improve the Earth's environment.

A recent ISEC study showed how the strengths of Space Elevators enable missions of all types, while having minimal or no environmental effect on our planet? We believe that not only can Space Elevators do this, but also allows activities in space that will actually improve Earth's environment. This paper will show how the Space Elevator infrastructure:

1) is environmentally friendly - actually negative carbon footprint,
2) eliminates excessive rockets launches that cause environmental damage, and
3) enables important Green Missions.

Indeed, this study showed the remarkable characteristics of Space Elevators leading to recognition that they are "Massive Green Machines."

1.1 ***Appropriate Space Access Architecture for Mars:*** When looking at the Moon and our dreams of spaceflight, we forget how extremely difficult it was to accomplish, both in energy and design complexity. Tsiolkovsky's remarkable rocket equation consumes so much mass to achieve orbit that it has greatly restricted what we can do. Now that we have decided to go to the Moon and on to Mars in a combined international, governmental and commercial effort of great magnitude, we need to expand our vision of 'how to do it.' It would seem that the establishment of a more robust infrastructure with reusable rockets and permanent Space Elevators must be developed. The multiple destinations, complexity of orbits, magnitude of each transition to orbit, and infrequent launches currently means that the difficulty of fulfilling the dreams of the many is a monumental "reach." Expanding space access architectures to include Space Elevators will enable a robust movement off-planet. Space Elevators will not be ready for humanity's initial migration off-planet. However, once colonies are established on the Moon and Mars using rockets, Space Elevators will enable robust growth by moving massive amounts of cargo, daily, inexpensively, environmentally friendly, and routinely. The essence of this article is that the two methods of achieving our dreams in space are complementary and compatible rather than competitive and significantly less environmentally damaging.

Rockets to Open up the Moon and Mars with
Space Elevators to supply and grow the Colonies.

Three principle strengths are inherent in rocket operations: 1) they are working today, 2) they can reach multiple orbits, and, 3) they provide rapid movement through the radiation belts for people. Essentially, we see Space Elevator strengths as permanent infrastructures that lead to daily, routine, environmentally friendly and inexpensive departures towards any mission destination. These inherent capabilities of Space Elevators result in what is a permanent bridge to outer space. Once a Space Elevator has been installed and upgraded to its initial capability, it will be there for a very long time, similar to roads, bridges and train tracks. Rising from the surface of the ocean to the Apex Anchor is accomplished with external power - such as solar energy. In contrast to rockets, Space Elevators are significantly carbon negative and contribute to the betterment of the Earth's atmosphere from the missions enabled, as well as by reducing rocket launches.

1.2 *Background - Galactic Harbour Architecture:* The Galactic Harbour is the unification of transportation and enterprise. From an engineering aspect, the Galactic Harbour is the combination of the Space Elevator Transportation System and the Space Elevator Enterprise System. The Galactic Harbour will be the volume encompassing the Earth Port while stretching up in a cylindrical shape to include two Space Elevator tethers outwards to GEO and beyond to the Apex Anchor.

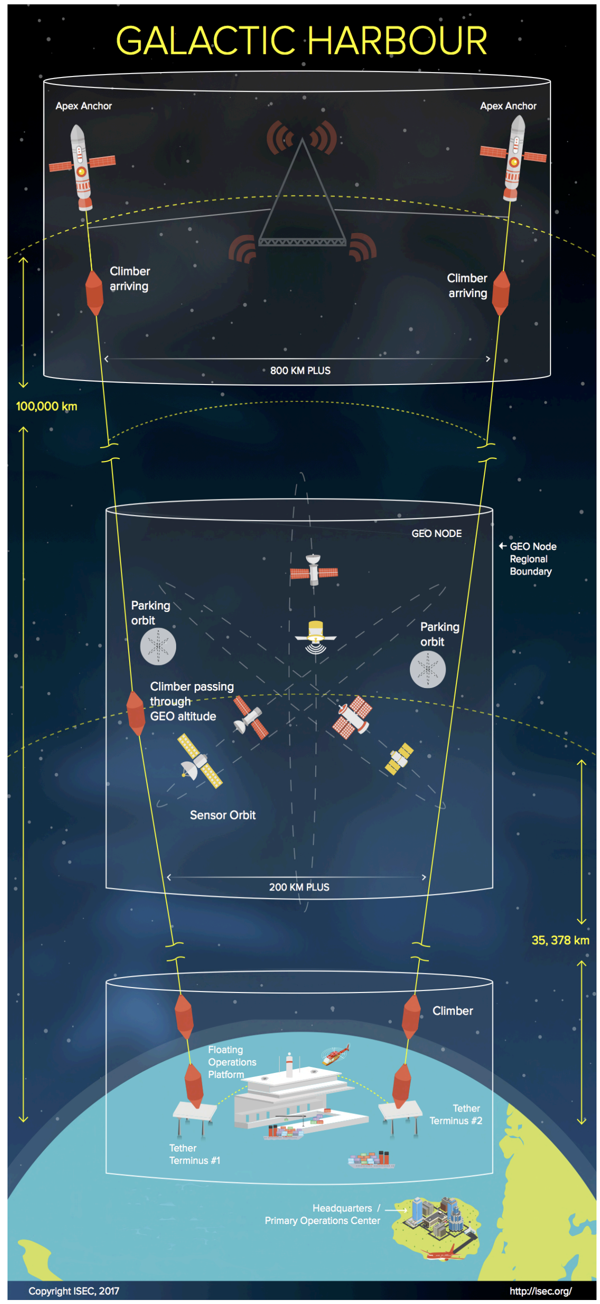

Figure 2, Galactic Harbour

Customer product/payloads will enter the Galactic Harbour at the Earth Port and exit some place up the Tether. The Transportation System is the “main channel” of the Galactic Harbour, moving cargo from the Earth Port to transportation locations within the Harbour; i.e. the GEO and Apex Anchor Regions.

1.3 Galactic Harbour Vision: The Space Elevator story is still being written. The Apex Anchor is where the Galactic Harbour meets the shoreline of outer space and where the "Transportation Story of the 21st Century" meets the "Final Frontier." This will include: "a network of Galactic Harbours. This mature Galactic Harbour transportation infrastructure will consist of three (or more) Galactic Harbours distributed around the equator with two Space Elevators within each. The capability to transport 79 metric tonnes per tether climber per day will have matured during the developmental phases. The possibilities for further growth are endless."[1]

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[1] Swan, P., C. Swan, M. Fitzgerald, M. Peet, J. Torla, V. Hall, "Space Elevators are the Transportation Story of the 21st Century," ISEC Study Report, www.lulu.com, 2020.

[2] Mankins, John webinar entitled " NSS Space Forum on 20 August - A Case for Space-Based Solar, Power.

[3] Mankins, John, conversation with P. Swan at IAC Washington DC Oct 2019.

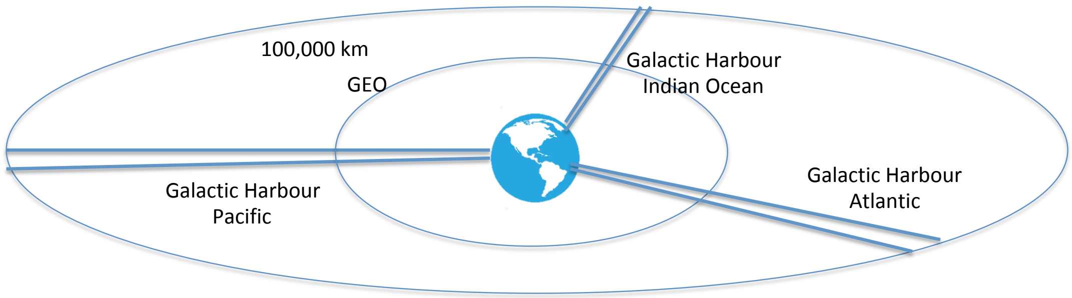

Figure 3, Three Galactic Harbours

1.4 Massive Throughput: When assessing the demands of customers for delivery to mission orbits, the strengths of Space Elevator show their dominant characteristic - delivery of massive cargo to orbit. In the study "Space Elevators are the Transportation Story of the 21st Century," calculations showed the total throughput for six Space Elevators inside three Galactic Harbours ends up with 170,000 metric tonnes delivered to GEO and beyond each year. This buildup chart shows the maturation from one Initial Operational Capability Space Elevator to three Galactic Harbours with mature Space Elevators.

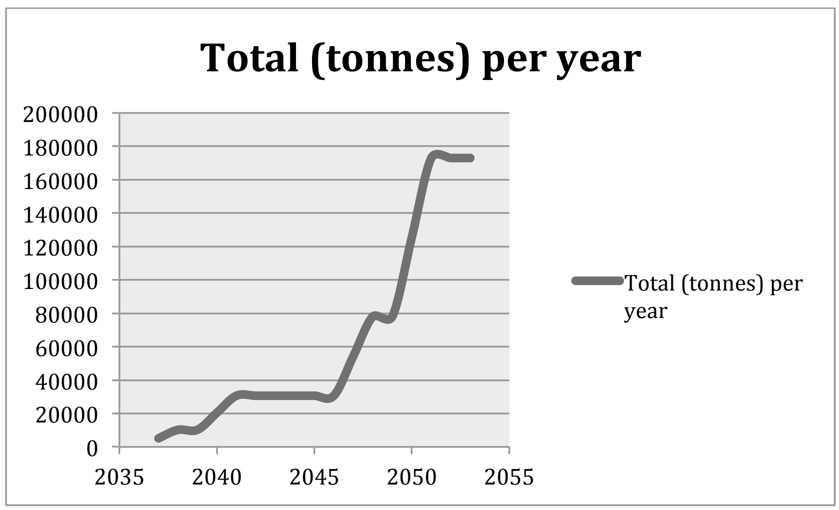

Figure 4, Total Tonnes to GEO and Beyond

2.0 Results from ISEC Research:

2.1 Completed Research: The topic of Space Elevators and how they fit into the future has been continuously addressed over the last ten years through numerous technical studies. This development of a large body of knowledge is shown by the titles of the studies conducted by the International Space Elevator Consortium, the International Academy of Astronautics, and the Obayashi Corporation.

Table 1, Study Summaries, ISEC

Year	***Title of ISEC Yearly Study Reports (www.isec.org/studies)***
2021	Design Considerations for the Space Elevator Climber-Tether Interface - just starting
2021	Beneficial Environmental Impacts of the Space Elevator - in work
2020	Space Elevators are the Transportation Story of the 21st Century
2020	Today's Space Elevator Assured Survivability Approach for Space Debris
2019	Today's Space Elevator, Status as of Fall 2019
2018	Design Considerations for a Multi-Stage Space Elevator
2017	Design Considerations for a Software Space Elevator Simulator
2016	Design Considerations for Space Elevator Apex Anchor and GEO Node
2015	Design Considerations for a Space Elevator Earth Port
2014	Space Elevator Architectures and Roadmaps
2013	Design Considerations for a Space Elevator Tether Climber
2012	Space Elevator Concept of Operations
2010	Space Elevator Survivability, Space Debris Mitigation

Table 2, Study Summaries, IAA & Obayashi Corporation

Year	***Title of ISEC Yearly Study Reports***
2019	The Road to the Space Elevator Era - IAA
2014	Space Elevators: An Assessment of the Technological Feasibility and the Way Forward - IAA
2014	The Space Elevator Construction Concept
	IAA - International Academy of Astronautics (https://iaaspace.org) Obayashi Corporation (https://www.obayashi.co.jp/en/news/detail/the_space_elevator_construction_concept.html)

2.2 Environmental Benefits from Space Elevators:

Carbon negative Space Elevators will contribute to the betterment of the Earth's atmosphere from the missions enabled, as well as the reduction of rocket launches. This section will summarize: how Space Elevators will enable Massive Green Technology missions, improving the Earth and its environment. (Space Based Solar Power being a principle example). The following list shows various positive effects that make the Earth greener:

1. Space Based Solar Power - what would it take to completely power the Earth by space based solar power? (see example summarized below) Elimination of coal burning plants would be achieved.
2. Nuclear Waste disposed towards Sun
3. Manufacture of graphene tethers will remove CO2 from the atmosphere (6,300 tonnes per space elevator x 6 or 37,800 tonnes in stable solid Carbon atomic state)
4. Future missions will require fewer rocket launches while increasing our capability in space with concepts such as being able to recycle and repair satellites
5. Practical logistical support for Mars or Moon colonies without using rockets to escape Earth's gravity well

As humanity decides to conduct off planet activities, there is a tremendous need for logistical support, movement of manufactured goods as well as transporting people. The question on the table is: how can Space Elevators accomplish this while having minimal or no environmental effect on our planet?

Space Based Solar Power (SBSP) Example: The Space Elevator is the only method that can enable a timely completion of this massive program. A SBSP program can eliminate 100's of environmental damaging coal plants. The potential of a SBSP program's environmental impact was explained by Dr. John Mankins: "an extensive SBSP program can stop global warming and possibly even reverse it."[2] Dr. Mankins estimates the project needs 5,000,000 tonnes of project spacecraft moved to geosynchronous orbit to achieve the desired effect of supplying global electrical demand for 12% of the population by 2060.[3] Using the Space Elevator transportation infrastructure, with daily, routine, safe, environmentally friendly, and inexpensive capabilities, the delivery will take only 28 years across their development. Rockets would require hundreds of launches across hundreds of years to meet this customer demand. A conclusion in this study showed that SBSP can only be done by Space Elevators moving a large amount of mass from Earth's surface to GEO. SBSP's approach can be realized for the betterment of all mankind leveraging the strengths of Space Elevators. The strengths of this "greener" approach to constructing SBSP also enables SBSP's greening of the Earth through the elimination of numerous coal burning plants.

2.3 Space Elevators Enabling Greening of the Earth: The study group believes many of the space activities currently being discussed can be done much easier, less expensively, and greener with Space Elevators. The study team also reviewed the current approach for High Level Nuclear Waste (NW) disposal and realized that Space Elevators can dispose of it permanently with little or no risk. Another "Greening Technology" program is the placement of large sun shields or shades in space to reduce a portion of solar energy from reaching Earth - thus reducing global warming. Massive payloads could distribute significant sun blockage at the Sun-Earth L1 location resulting in less solar energy impacting the Earth's atmosphere.

2.4 Environmental Impact from Construction and Operations of Space Elevators: This topic explores the environmental impact of manufacturing, building and operating a Galactic Harbour Permanent Transportation System. However, it must also be pointed out that Space Elevator operations have virtually zero impact on the environment. This is because there are no effluents from the power usage nor impacts from the source of power (Solar power to solar cells to electric motor driven wheels for driving upward on a tether track). The lift-off and climb of the tether climber to the Apex Anchor is all electrical and does not impact the environment. This ability to raise mass with electricity defeats the catastrophic rocket equation and enables Earth friendly liftoffs daily from
the six Space Elevators around the equator, inside three Galactic Harbours. The number of rocket launches needed to place equivalent payloads to GEO, would have a significant impact on the environment while space elevators would be almost totally green in both construction and operations.

Statement of the Problem: **W**hat effect will the building, operation and maintenance of the Galactic Harbour concept would have on the Earth's environment. When a full environmental study is conducted, each of the major segment developments must be evaluated separately: Earth Port, Tether Climber, Tether, GEO Node, and Apex Anchor. One interesting environmental aspect of the development of the full Space Elevator is the manufacture of the tether (using single

[2] Mankins, John webinar entitled " NSS Space Forum on 20 August - A Case for Space-Based Solar, Power.
[3] Mankins, John, conversation with P. Swan at IAC Washington DC Oct 2019.

crystal graphene). Depending on how 100,000 km of sheets of graphene are produced, it could pose an environmental impact at the manufacturing site. One positive aspect is the development of each Space Elevator Tether would sequester 6,300 metric tonnes of carbon into inert carbon structures for each tether. Given the major sections of the Galactic Harbour permanent transportation system, the only section that would have a potential localized impact on the Earth's environment would be the Earth Port, however minimal it would be. However, its impact would be no greater - and possibly much less - than the building and operation of a large oil platforms without the risk of major oil leakage from underwater drilling.[4] The bottom line is that the Space Elevator will create a transportation infrastructure that will provide revolutionary routine access to space, inexpensively, safely, daily, and with large payloads. It's design, construction and operation, from the start, will be environmentally friendly.[5]

2.5 Environmental Impact from Construction and Operations of Future Rockets: The construction and operation of launch facilities and rocket production plants have been studied extensively. The final answer within each of the environmental impact statements reflect the necessity of having a launch capability while seeing minimal effects due to infrequent launching of any one type of rocket. However, as the massive movement to space begins with hundreds to thousands of launches, the studies will be left behind in the environmental dust. An example is the SpaceX StarShip which will be able to move 100 tonnes to LEO, and advertises 21 tonnes to GEO without refueling. Each launch could leave contamination at the launch site, impact the atmosphere, stratosphere and more with its combustion while also adding to the space debris in LEO. To accomplish a launch to LEO, a rocket burns huge amounts of fuel in the atmosphere. This has been shown to be "not healthy" for the atmosphere while being very inefficient. A recent statement was made reference to this problem.

> "Currently rocket launches contribute minimally to climate change, both in terms of greenhouse gas emissions and depletion of the Earth's ozone layer. However, trends in the global manufacturing of launch vehicles show that the industry's commercialization will lead to a drastic increase in the frequency of rocket launches in the coming decades. Companies around the world are seeking to develop competitive capabilities, driving down the time of the production and launch cycle. With more regular launches, the emission of black carbon and alumina from rockets will begin to comprise a larger percentage of causes of ozone depletion. The drastic effects that this could have on the environment are largely un-researched, and legislation concerning the environmental impacts of rockets do not always attempt to mitigate these emissions' impacts."[6]

The current belief is often expressed as something like - The current rate of rocket launches has a negligible effect on the environment. However, if the frequency is to increase in line with the industry's ambitions, including a significantly streamlined manufacturing cycle and potentially establishing a settlement on Mars, this will not be the case. Reusable vehicles may offer a plan to minimize pollution; but, as shown, these are not guaranteed to become an industry standard. In addition, huge numbers of launches will still be going through the atmosphere, contaminating the land around the launch site and the atmosphere along its path, leaving parts of rockets and spacecraft in orbit, and consuming natural resources in large quantities. When one looks at the list of projected missions and the demands for mass to orbit, one can understand why Mr. Musk

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[4] Penny, Robert; Hall, Vern; Glaskowsky, Peter; Schaeffer, Sandee; "Design Consideration of a Space Elevator Earth Port: A Primer for Progress in Space Elevator Development," ISEC Position Paper # 2015-1

[5] Penny, Robert; Hall, Vern; Glaskowsky, Peter; Schaeffer, Sandee; "Design Consideration of a Space Elevator Earth Port: A Primer for Progress in Space Elevator Development," ISEC Position Paper # 2015-1

[6] (Phister, correspondence)

said he would like three launches a day of his massive Star Ship to support his colony on Mars. It would seem reasonable that if he is successful with this vision and mission, his competitors around the world will also be launching often, expensively, and aggressively supporting various missions to GEO and beyond. The projected demand for tonnes to orbit is shown in Figure 5.

Figure 5, Delivery Demand (IAA Study, 2014)

Demand in Metric Tons	2031	2035	2040	2045
Space Solar Power	40,000	70,000	100,000	130,000
Nuclear Materials Disposal	12,000	18,000	24,000	30,000
Asteroid Mining	1,000	2,000	3,000	5,000
Interplanetary Flights	100	200	300	350
Innovative Missions to GEO	347	365	389	400
Colonization of Solar System	50	200	1,000	5,000
Marketing & Advertising	15	30	50	100
Sun Shades at L-1	5,000	10,000	5,000	3,000
Current GEO satellites + LEOs	347	365	389	400
Total Metric Tons per Year	58,859	101,160	134,128	174,250

3.0 Comparison of Journeys: When embarking on a long journey, each of us thinks about the destination first. However, to have a successful journey, one must also consider the other factors that will be impacted; such items as: cost, travel time, environmental impact, availability, value delivered, safely and resource efficiency.

Concept: When Space Elevators are ready, the factors influencing movement of mission payloads will not be dominated by resource consumption and environmental impacts.

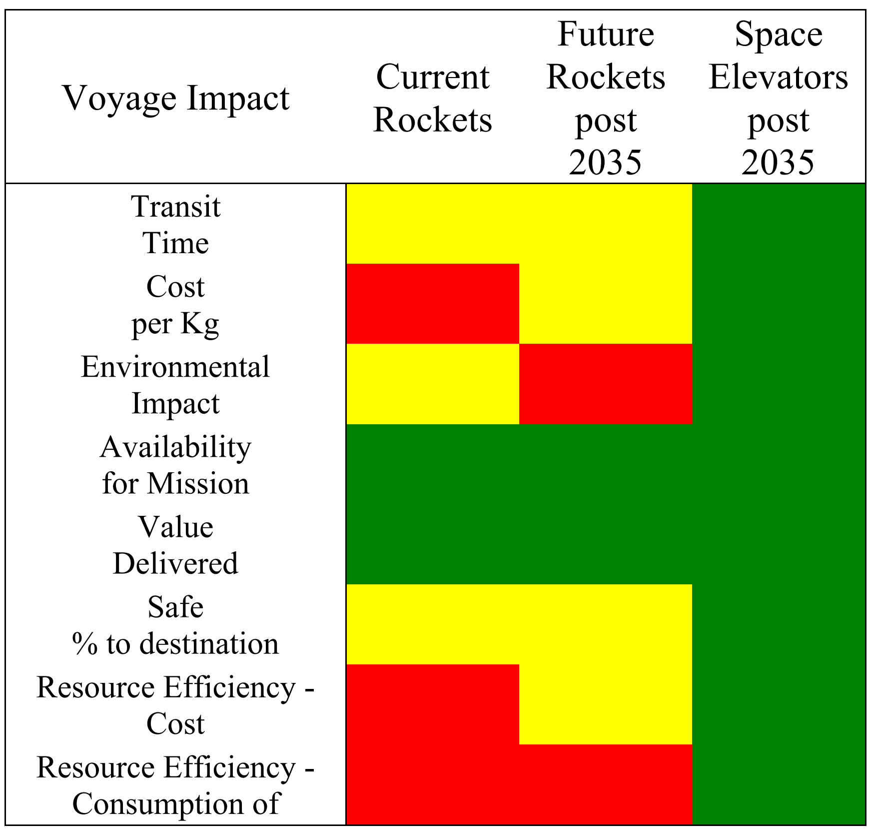

Figure 6 Comparison Rockets and Future Space Elevators

One message from this analysis is that if there are thousands of launches per year to support our future missions to Mars alone, then the impact will be far from trivial. In addition, just by the reality of the rocket equation, that approach consumes precious resources in great quantities. The example of the Apollo mission is illuminating: Apollo placed only one half of one percent of the original launch pad mass onto the surface of the Moon - illustrating the complexity of missions leveraging rockets against the Earth's gravity well. The study authors concluded that, the future will lead to rockets leveraged for special cargo, special orbits and movement of people. Space Elevators will do all the heavy lifting and routine delivery of cargo.

4.0 Conclusion: The net assessment trade study conducted by ISEC showed that:

> Space Elevators and Galactic Harbours are Big Green Machines designed to improve the Earth's environment through two significant contributions. The first is the remarkable "zero-emission" lift of cargo to space - reducing environmental impacts from rocket launches. The second is the ability to deploy massive systems to GEO that can actually improve the Earth's environment.

As such, the utilization of Space Elevators will be significantly positive with respect to environmental impacts, even when customer demands reach hundreds of thousands of tonnes of mass each year. The conclusion seems to be that there will be huge numbers of launches occurring each year in the future to support humanity's missions unless Space Elevators are developed in the very near future. A recent ISEC study report showed that the Space Based Solar Power system requires 5 million metric tonnes of support to GEO while Mr. Musk has stated he needs one million metric tonnes to Mars. To accomplish these exciting missions of critical importance to humanity, there with be unprecedented numbers of launches (yes, less expensive and more efficient in operations) leading to undetermined environmental impacts. This expected huge numbers of launches will still be going through the atmosphere, contaminating the land around the launch site and the atmosphere along its path, leaving parts of rockets and spacecraft in orbit, and consuming natural resources in large quantities. Many environmental studies have been conducted but for limited projection of launches. They did not look towards the future, and "the impact has not been addressed for large numbers of launches." A statement that illustrates this concept is:

> "a recent study showed that the level of environmental impact of black carbon is currently equivalent to the release from all aircraft flying around the globe.[7]"
>
> and
>
> "With more regular launches, the emission of black carbon and alumina from rockets will begin to comprise a larger percentage of causes of ozone depletion. The drastic effects that this could have on the environment are largely un-researched, and legislation concerning the environmental impacts of rockets do not always attempt to mitigate these emissions' impacts.[8]"

Of course the future is unknown; but, projections must take into account the impacts on the environment of potential hazards of hundreds or even thousands of launches per year. Each of those "done in the future" studies must be conducted for the global environment, not locally, nor for a single launch vehicle. An example is the study of black carbon that has not been researched

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[7] In 2018, rocket engines emitted 10,000 tons of black carbon and aluminium particles into the stratosphere, about the same annual amount caused by global aviation (9,500 tons). Levykin, Volodymyr, "Going Green: Why the Launch Industry Urgently Needs Environmental Regulations," ViaSatellite Podcast, Aug 19, 2020.

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as it is a small effect for one launch when addressed locally. Looking at the impact of black carbon on a global scale with hundreds of launches, the conclusion will be quite different. This is just one topic for concern that must be expanded to include a total environmental study across the globe for hundreds of launches per year.

5.0 Realization: A Dual Space Access Architecture combining rocket and space elevator strengths results in tremendous advantages in the "greening of the Earth." The first is the rapid transit through radiation belts with people as rockets are not being wasted on logistics. The second is that all the robotic movement of mass (cargo, habitats, air, water, etc) would be moved safely, routinely, daily, environmentally friendly, and inexpensively by Space Elevators. This separation of delivery approaches will greatly enhance missions in the future. As customer demands for huge masses matures to support near term missions such as Space Based Solar Power (five million tonnes to GEO) and a Mars Colony (one million tonnes to Mars), the value of Space Elevators becomes obvious. When the Space Elevator delivers 80% of the mass needed for a critical missions, the savings in cost, time and environmental impact will make us ask: Why not sooner?

6.0 Recommendation - Conduct global and future launch flotilla studies

As shown in the conclusion, there will be hundreds, or even thousands, of rocket launches in the not to distant future to support the dreams and plans for Space Based Solar Power and Missions to the Moon and Mars. This increase from roughly 100 launches per year to thousands across the globe could be sooner than we think. These operational conditions have NOT been assessed in the sense of three factors:

- Local surface contamination surrounding a active launch facility,
- Atmospheric to Lower Space region pollution such as "black carbon" driving the problem of Ozone depletion
- Increase in space debris left in Low Earth Orbit.

The dreams of many must be protected, which means full understanding of the impact of hundreds to thousands of launches per year. A global study must be initiated as the impact is not limited to local, and infrequent, liftoffs. This knowledge would greatly support the concept of a Dual Space Access Architecture.

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