Life cycle assessment of proposed space elevator designs

Tyler M. Harris*, Pragnya L. Eranki, Amy E. Landis

Department of Civil and Environmental Engineering, Colorado School of Mines, Coolbaugh Hall, 1012 14th Street, Golden, CO, 80401, USA

ABSTRACT

The cost and design requirements for transporting satellites and payloads to space using existing orbital technology remain prohibitively high. Yet, quantitative sustainability assessments to evaluate system costs and impacts of existing and proposed orbital transportation systems have been rare. Space elevators are a proposed orbital transportation system intended to safely, gently, and inexpensively transport satellites and other payloads to and from space on a routine daily basis. This life cycle assessment (LCA) was completed to quantify, assess, compare, and suggest improvements to the potential environmental and financial performance of three proposed space elevator system designs, namely i) a One-Tether Initial Space Elevator (the base design) ii) a Two-Tether Initial Space Elevator iii) an Additional One-Tether Space Elevator. A sensitivity analysis to compare the impact of reduced utilization capacity of the space elevator system was also performed. Results indicated the Additional One-Tether Space Elevator scenario had the lowest environmental impact, while the Two-Tether Initial Space Elevator scenario had the lowest production cost per unit mass delivered to orbit. This LCA identified system elements for targeted impact reduction, e.g. operational impacts could be significantly reduced by improving the sustainability of terrestrial transportation delivery systems to the space elevator port. Sensitivity analysis results showed producer cost to be the only impact category with a direct inversely correlated response to reduced capacity; all other impacts showed less sensitivity to utilization reduction. Ultimately, the proposed space elevator design was found to be an environmentally and financially sustainable option for orbital transportation. Further application and refinement of such sustainable engineering and quantitative sustainability assessment methodologies to spacecraft, rocket, and other existing and proposed orbital transportation systems and industries is highly recommended.

1. Introduction

The average cost to transport material from Earth's surface to space has been roughly $20,000 per kilogram [1] with the global space economy accounting for $323 billion of economic activity in 2015 [2]. However, other proposed and well-studied orbital transportation systems such as the space elevator could drastically reduce the cost and design requirements for payload delivery to orbit. The space elevator design presented by Swan et al., in 2013 has an estimated cost to geosynchronous earth orbit (GEO) of $500 per kilogram [3]. Yet quantitative sustainability assessment research of any existing or proposed orbital transportation systems is absent in the current literature.

Design and development of nascent technologies are improved by quantitative sustainability engineering methodologies such as life cycle assessment (LCA). LCA is a vetted and standardized engineering methodology that quantifies and assesses the environmental impact of a product, service, process, or activity throughout its life-cycle. The life cycle impact assessment (LCIA) portion of an LCA examines

environmental impacts and anticipates impact tradeoffs and unintended consequences. These LCA methods and tools have international standards for proper studies and several international associations and journals devoted to its use and continued development. Managing impacts and tradeoffs using LCA also regularly reduces cost and improves system performance. This research performed an environmental LCA of a space elevator orbital transportation system to quantify, assess, and improve the environmental and overall performance of the proposed design.

A hybrid LCA that combines process-LCA and economic input-output (EIO)-LCA methods was used in this study. Process-LCAs utilize and tally large datasets including emissions, flows, and resource usage for each process in the system, whereas EIO-LCA results rely on sector-level averages. Hybrid LCAs utilize both methods in various combinations; for this study a process-LCA model was built first, and missing data were supplemented with EIO-LCA data. A sensitivity analysis of the LCIA results to changes in capacity utilizations was performed. Uncertainty was evaluated via a pedigree matrix and the overall

* Corresponding author.
E-mail addresses: tmharris@mines.edu, tyler.harris@pnnl.gov (T.M. Harris).

scenario analysis addressed elements of both uncertainty and sensitivity. When more data become available, Monte Carlo analysis is advised. The functional unit for the cradle-to-gate scope was one complete space elevator system deployed and ready for operation, and the functional unit for the cradle-to-use study was 1 kg (kg) transported from the Earth's surface to geosynchronous Earth orbit (GEO).

Space elevators would deploy/collect satellites to/from any of Earth's orbits, as well as deliver and receive payloads to/from cislunar or interplanetary space [4]. The Hubble Space Telescope and International Space Station (ISS) are in low earth orbit (LEO) < 1,000 km altitude, Global Positioning System (GPS) satellites are in a medium earth orbit (MEO) ~ 22,000 km altitude, and weather/communication satellites are commonly in GEO ~ 35,800 km – the minimum high earth orbit (HEO) that maintain their positions in orbit relative to a spot on the Earth's surface. Payload to GEO accounts for less than 12% of the total mass at liftoff for existing rocket technologies. The space elevator payload to GEO was designed to account for 70% of the total space elevator climber departure mass (including its renewable power source). Because of the slow initial space elevator travel times, human travel to/from orbit will likely continue to utilize existing rocket orbital transportation technologies for the foreseeable future. The space elevator design includes a total of 7 tether climbers each operational space elevator tether for regular daily payload departures and arrivals. Estimates on the cost to deliver payloads to and from GEO from various space elevator concepts and designs ranged from $100 to $1000 per kilogram [5].

The space elevator is an Earth-satellite tethered (space-tether) system connecting a counterbalance in far earth orbit (100,000 km altitude) to an offshore platform on the Equator by a large carbon nanofiber (CNF) ribbon or tether (Fig. 1). The orbiting *counterbalance satellite node* provides tension to the *CNF tether* through centrifugal forces, while the surface *anchor node* (and tether system center of mass) holds the counterbalance satellite node in GEO via centripetal forces [3]. Space vessels called *tether climbers* then traverse the taut CNF tether, delivering payloads to a *GEO satellite node* for final payload delivery to GEO and other desirable Earth orbits.

The development of graphene, carbon nanofibers, and nanotubes in the late 1990s and 2000s made the space-tether elevator concept technically feasible [6]. Space elevator development has been supported by the International Space Elevator Consortium (ISEC) since 2008, carrying forward the substantial research established through NASA. There have been numerous international competitions on various aspects of space elevator design, and it has been proposed as a "cleaner, greener alternative [to rocketry] that would be entirely reusable, and only require a one-time assembly … and could theoretically provide humanity with cheap, routine, effective, daily, clean, and virtually risk free access to space" [5]. As of 2018, at least two for-profit companies (LiftPort Group and Obayashi Corp), as well as the Japanese Space Administration were actively developing a space elevator design for near-term deployment [6,7].

The substantial portion of the space elevator mass is the approximately 50 metric tons of 10,000 km long CNF tether, however, approximately 32 metric tons of control fuel for initial tether and counterbalance deployment must be launched via rocket into orbit [3]. The CNF tether would be manufactured on Earth primarily from hydrochloric acid and benzene, then launched to GEO for initial deployment. The orbiting tether would then be extended towards the surface of the Earth as the counterbalance is propelled to the final 10,000 km orbit, all while maintaining a geosynchronous orbital position. Once the tether is attached and reinforced, a series of 7 tether climbers can then begin the 7-day each way trips each day carrying 14 metric ton payloads at a time.

A carbon nanotube LCA provided life cycle inventory (LCI) data, i.e. upstream and downstream energy and material flows, for each kilogram (kg) of carbon nanotube product produced [8]. The remainder of the space elevator design parameters and LCI data required for this study were collected from Swan et al. (2013). It must be noted that the carbon nanofiber/nanotube technology required for successful production and deployment of the space elevator design studied herein was still in development at the time of this study [5], therefore, the results and findings developed and presented were the best available but may not fully represent the life-cycle impacts of a deployed CNF tether and
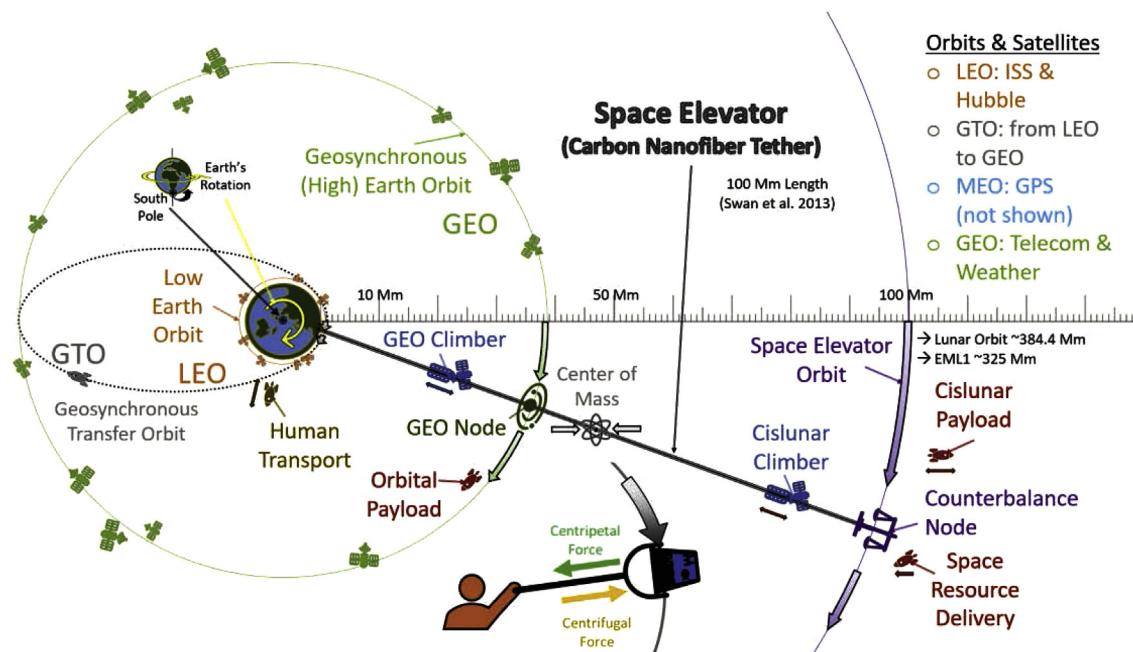
Fig. 1. Simple Map of Earth Orbits with Idealized Space Elevator System. The proposed space elevator design by Swan et al. (2013) is a 100,000-km carbon nanofiber tether [black line] in geosynchronous earth orbit (GEO) [green orbit] with a GEO Node [green] attached to an anchor node offshore platform near the equator held taunt through centrifugal force by an orbiting counterbalance node [purple] and traversed by solar powered tether climbers [blue] delivering payloads [red] to and from orbit and cislunar space. Centripetal and centrifugal forces hold the tether taunt and nodes in place. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

space elevator.

This study quantified the potential environmental impacts of the production, deployment, and use of a space elevator using LCA. This study was the first of its kind; at the time of completion there were no LCAs or sustainability assessments of any earth-to-orbit technologies including the space elevator. The use of this valuable quantitative sustainability assessment tool (i.e. life cycle assessment or LCA) and its applications in assessing the environmental sustainability of emerging space technologies was detailed and documented herein. Furthermore, as interest in the commercial research, development, and utilization of space resources continues to increase, humankind has a rare opportunity just prior to a period of rapid technological development – to prevent potentially severe unintended consequences and reduce negative impacts through application of quantitative sustainability assessments such as with this research.

2. Material and methods
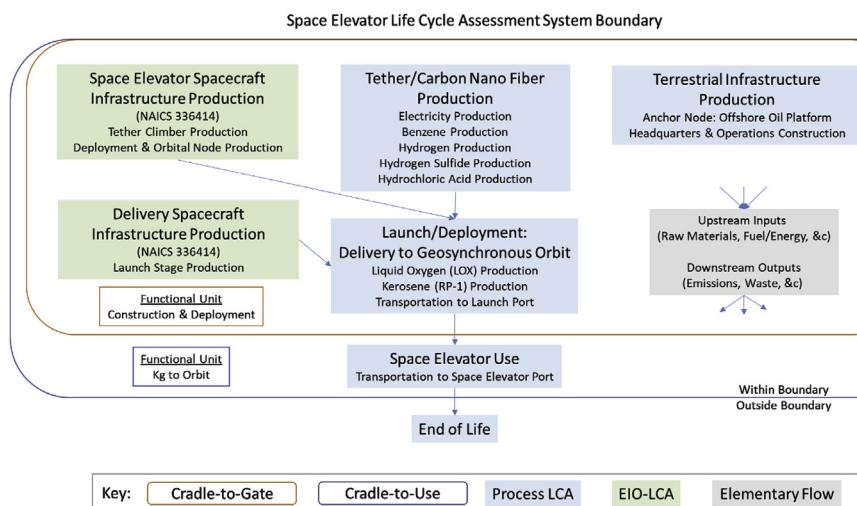
Life Cycle Assessment (LCA) is a method used to quantify the environmental impacts of a product or process throughout its entire lifetime, from raw materials extraction, including production, use and ultimately through end-of-life. The process-LCA methodology is defined by the ISO 14040 series, and includes four steps: 1. Goal and scope definition, 2. Life Cycle Inventory (LCI), 3. Life Cycle Impact Assessment (LCIA), and 4. Interpretation and improvement [9,10]. LCAs start with an explicit statement of the goal, scope and system boundaries of the study. The second step, LCI, is the most data intensive part of an LCA, where all of the inputs and outputs for the product are quantified. The third step, LCIA, converts and presents the inventory data in meaningful terms, such as global warming potential, energy return on investment, and ecosystem impacts. The details of these steps are outlined in the materials and methods section below. Finally, in the interpretation step, covered in the results and discussion section, the findings of the LCA are evaluated in relation to the defined goal to develop conclusions and make recommendations.

Instead of only process-LCA, an attributional hybrid LCA was employed in this study, because of the nature of emerging technologies such as the space elevator. Attributional LCAs quantify and assess environmental impacts from each activity, product, or method (i.e. unit and system processes) included in the system boundary. Because research on the sustainability of orbital transportation systems and the space industry is rare, EIO-LCA methodology was used for all spacecraft production processes in the model. Economic input-output LCA (EIO-LCA) is an alternate method for performing LCA by determining the average environmental impact per dollar spent in a specified industrial classification. This EIO-LCA methodology was developed and maintained by researchers at Carnegie Mellon University (CMU), and utilizes linear algebra based on Leontief economic principles [11,12]. It estimates environmental emissions resulting from economic activities (i.e. purchases) in the major sectors of the economy using input-output tables derived from the Bureau of Labor Statistics [13]. Whereas process-LCA (described in the preceding paragraph) allocates impact potentials from extensive LCA databases containing all the system's upstream material, energy flows and emissions, collecting and sharing such LCA databases is a resource intensive endeavor; furthermore, some products, processes, and services do not have such datasets available. In such cases, hybrid LCA methodologies can be used to establish a process-LCA model while filling any gaps in the LCA databases with EIO-LCA results.

In this study, scenario analysis was used to compare various configurations of the space elevator design and business plan, and corresponding transportation and utilization capacity use phase estimates (Table 1). Three space elevator design configurations/business plans were presented by Swan et al. (2013): 1-Tether Initial Space Elevator, 2-Tether Initial Space Elevator, and Additional 1-Tether Space Elevator; these configurations were evaluated in this study for both cradle-to-gate and cradle-to-use scopes. The 1-Tether Initial Space Elevator scenario

Table 1
Space elevator design scenario and sensitivity analyses parameters and use-phase transportation and utilization estimates.

| Scope	Scenario Name	Scenario Details	# Ports	# Tethers	# Climbers	# Anchors	Rocket Launch Mass (kg)	Design Capacity/Modeled Capacity (kg to Orbit/Year)	Surface Transport Distance to Port (km)	Capacity Utilization (%)
Cradle-to-Gate (& Cradle-to-Use) Scenario Analysis	One-Tether Initial Space Elevator	Base Technical Design	1	1	7	2	86,000	5,096,000/5,096,000	10,019	100%
	Two-Tether Initial Space Elevator	Indorsed Business Plan	1	2	14	4	86,000	10,192,000/10,192,000	10,019	100%
	Additional One-Tether Space Elevator	Base Design Deployed w/ Previous Space Elevator	1	1	7	2	0	5,096,000/5,096,000	3,340	100%
Cradle-to-Use Only Sensitivity analysis	90% Utilization One-Tether Initial Space Elevator	Base Design w/90% Utilization	1	2	14	4	86,000	5,096,000/4,586,000	10,019	90%
	50% Utilization One-Tether Initial Space Elevator	Base Design w/50% Utilization	1	2	14	4	86,000	5,096,000/2,548,000	10,019	50%
	10% Utilization One-Tether Initial Space Elevator	Base Design w/10% Utilization	1	2	14	4	86,000	5,096,000/509,600	10,019	10%

Space Elevator Life Cycle Assessment System Boundary

was the primary technical design configuration, or base design, while the 2-Tether Initial Space Elevator scenario represented the recommended business plan configuration. The Additional 1-Tether Space Elevator scenario represents future space elevator systems deployed with a previous space elevator (without the need for initial rocket deployment).

Capacity utilization is the proportion of designed capacity actualized in use [capacity utilization = (actual output/potential output) * 100%]. To evaluate the three primary designs discussed and presented in Swan, cradle-to-use scope capacity utilization was evaluated at 100%. Therefore, sensitivity analysis was used to evaluate three alternate utilization capacity cases in the cradle-to-use scope: 90% Utilization of the 1-Tether Initial Space Elevator, 50% Utilization of the 1-Tether Initial Space Elevator, and 10% Utilization of the 1-Tether Initial Space Elevator scenarios. These three alternate utilization capacity sensitivities were evaluated using the 1-tether space elevator base technical design (100% utilization); 90% capacity utilization was used to evaluate the base scenario's sensitivity to a 10% reduction in annual/lifetime utilization, and so on. The expected increase in cradle-to-use impacts from a given percent utilization was given by a negative-one-power-function (expected impact % increase = % utilization^{-1}).

The annual payload delivered to orbit with the 10% capacity utilization 1-tether space elevator would be approximately 510 metric tons per year. 108.2 metric tons was launched into space in 2017, with the Federal Aviation Administration (FAA) forecasting 137 tons launched in 2018 [14]. This puts annual payload to orbit for the 10% utilization scenario within an order of magnitude of the current orbital transportation system rate.

The space elevator can deliver payloads and satellites to almost any of Earth's orbits, however, geosynchronous earth orbit (GEO) was considered the primary destination orbit of space elevator payloads. In that respect, whenever the term *orbit* has been used without specific orbital designation, it should be taken as reference to GEO. Transportation and shipping distances of payloads to the space elevator from their points of origin were assumed uniformly distributed around the globe. Furthermore, most space elevator designs recommend the anchor node, or space elevator terrestrial port facility, be located near the equator. Since the world's population is normally distributed around the equator, the uniform distribution assumption holds. The circumference of the Earth at the equator is approximately 40,075 km, and thus 10,019 km the average transportation distance estimate for a single global space elevator port system [15]. This 10,019-km estimate is then multiplied by a third, to produce the 3,340 km estimate for the average transportation distance for an optimally placed second space elevator port system.

The methods section from this point forward is organized by each

major step of the LCA process. This paper evaluates the construction and use of the space elevator design proposed by Swan et al. (2013). In addition, this paper investigates impacts of additional scenarios and sensitivities for space elevator development and deployment.

2.1. Goal and scope

The goal of this LCA was to evaluate the life-cycle environmental impacts of a space elevator and to identify ways in which environmental benefits could be realized as space elevator technologies evolve; by doing this we identify areas during design and production where reductions in environmental impacts can be realized (aka hot spots). In addition, this LCA aimed to identify potential tradeoffs and unintended consequences of future space elevator production, deployment, and use. Two system scopes were evaluated in this LCA: the cradle-to-gate scope evaluated the construction and deployment of the space elevator, and the cradle-to-use scope evaluated and compared the construction, deployment and use of the space elevator with additional space elevator configurations. The environmental impact categories calculated and interpreted were global warming, eutrophication, acidification, ecotoxicity, ozone depletion, and smog formation potentials, as well as fossil fuel resource depletion and human health effects (namely carcinogenics, non-carcinogenics, and respiratory effects).

2.2. System boundary and functional unit

The system boundary (Fig. 2) included two overlapping scopes described in the previous section to allow for improved resolution and interpretation of results: a cradle-to-gate scope including production, construction, and deployment, with a functional unit of a complete space elevator system; and infrastructure and a cradle-to-use scope including production, construction, deployment, and use, with a functional unit of 1 kg safely transported from the Earth's surface to geosynchronous Earth orbit (GEO). The two system boundaries (cradle-to-gate in orange and cradle-to-use in blue) used in this study allowed for independent construction and deployment impact analysis, as well as a per unit mass delivered to orbit impact analysis. Best efforts were made to include all upstream and downstream impacts of the space elevator construction, deployment, and use within the scope. All assumptions and exclusions from the boundaries, including end-of-life were noted herein.

LCAs often do not include construction of major infrastructure because the impacts of construction amortized over the system lifetime are assumed to fall below a 1% cutoff criterion [12]. However, because the construction and deployment of a space elevator is of such a large scale and is a capital investment for future infrastructure, its associated

impacts were also included and considered. Though included in the scope and boundary, extensive analysis of the emissions from combustion of rocket fuel during launch was not possible in this study. The only impact category included for rocket fuel combustion at this time is global warming potential (GWP). This is because of the relatively simple calculation of CO_2 emissions from kerosene combustion. However, this does not account for any other emissions or impacts from rocket launch, including emissions throughout the height of the atmosphere as the rocket reaches orbit.

The end-of-life (EOL) was excluded from all system boundaries. Space elevator design inherently allows for ejection of the tether and orbital nodes into space causing minimal earth impacts in case of emergency. The design of the space elevator can also allow for the carbon nanofiber ribbon to be recycled in orbit thereby reducing the ultimate cradle-to-grave impact of the space elevator. Future studies should include this aspect of the full space elevator lifecycle.

2.3. Life cycle inventory (LCI)

All design specifications and scenario values were based on a recent comprehensive design for production, deployment, and use of a space elevator, as detailed in the book *Space Elevators: An Assessment of the Technological Feasibility and the Way Forward* [3]. This book compiles and expands on years of NASA funded research and academic publications by the book's authors [5,6,16–23]. Other LCI data values were collected via a thorough literature review and the use of existing LCI databases. Efforts were made to ensure the reliability and suitability of the data selected for the model. Minimal sustainability literature and data were located for this study; therefore, single point values with significant uncertainty were used. This LCA assumes that all values and datasets adequately represent the average for the variables and systems characterized. However, all data assumptions were made conservatively, i.e., biased towards increasing the associated impact as opposed to underestimating the potential consequences.

The space elevator design used this study was based on the 2013 Swan et al. study. This space elevator design includes the production, deployment, and use of two space elevators to improve the business case for the plan through economies of scale. The primary benefit of deploying the second and all subsequent space elevators is the lack of requiring the launching of roughly 86 metric tons of material into orbit for initial deployment. All space elevators following the first can be deployed into orbit using the previous space elevator. Table 2 shows the primary source data for the space elevator design used for this LCA. Primary inventory data was collected from the documented sources and was used to calculate the inventory reference flows per the declared functional units.

Hybrid LCAs use a combination of process data and EIO-LCA data to compile data for upstream processes. This study uses process data from ecoinvent version 3.1. EIO-LCA data was used from the USEIO-LCA database with a base year of 2002 with producer prices [24]. Cost data summarized in Table 2 was reported in 2013; these values were converted to 2002 (−22.8% cumulative rate of inflation) to match EIO-LCA input data (http://www.usinflationcalculator.com/). Table 3 shows the LCI system processes and modeling input parameters (i.e. inventory reference flows per function unit) with the associated LCA database for each process upstream dataset.

2.4. Life cycle impact assessment (LCIA)

Impact assessment was completed using TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts 2.1 V1.01) midpoint impact characterization methodology developed by the EPA for the US [25]. Midpoint impacts reflect environmental impact potentials, a link in the cause-effect chain, while endpoints reflect the effect itself [26]. The following 10 TRACI impact categories were calculated and interpreted: global warming potential

(GWP), eutrophication, acidification, ecotoxicity, ozone depletion, smog formation, resource depletion, and human health: carcinogenics, non-carcinogenics, and respiratory effects. GWP for example, is a tally of all upstream and downstream greenhouse gas emissions (GHG) including the three most influential GHGs, carbon dioxide, nitrous oxide, and methane measured in units of kilograms of carbon dioxide equivalent (kg CO2 eq.), throughout the specified scope. Other important impact categories include eutrophication potential which measures the nutrient overload on environmental systems that causes algal blooms and ecosystem dead zone measured in units of kilograms of nitrogen equivalent (kg N2O eq.) and particulate matter emissions causing severe human respiratory effects measured in units of kilograms of airborne particulate matter of 2.5-μm equivalent (kg PM 2.5 eq.). This LCI data along with process-LCA and EIO-LCA databases and TRACI LCIA characterization methodologies was used to provide system environmental impact performance findings and recommendations.

In addition to the 10 TRACI impact categories, a producer cost impact category was also calculated using the space elevator strategic investment layout presented in the Swan et al. study (2013) and listed in Table 2. Because the 2008 TRACI normalization factors do not include a producer cost impact category, the 2008 US national gross domestic product (GDP), $14.7 trillion, and 2008 US gross national income (GNI) per capita, $49,330, as reported by the World Bank [27] for a common reference benchmark normalization factor for the producer cost impact category. A preliminary producer cost-to-orbit estimate was established by taking the producer cost divided by the mass delivered to orbit ($/kg to GEO).

2.5. Uncertainty analysis

In addition to the scenario (3 space elevator configurations) and sensitivity (2 utilization capacities of the space elevator's base design) analyses described in previous sections, uncertainty analysis was completed via a pedigree matrix. A pedigree matrix is a method to quantify and evaluate the representativeness of the LCI data to the stated goals, as well as to examine the uncertainty as they relate to the final LCIA results. The five data quality indicators empirically determined from the "improved pedigree matrix" approach were: reliability, completeness, temporal correlation, geographical correlation, and further technological correlation [28]. The pedigree matrix in Table 4 and Table 5 have data quality scores and averages ranging between 1 (lowest quality) and 5 (highest quality).

The lowest quality indicator assigned was 2 (qualified estimates or data from related systems) in three processes, while there were sixteen 3's (mid quality data), thirty 4's (verified data) and five 5's (highest data quality). As more reliable and verified data becomes available, more detailed uncertainty analysis, including Monte Carlo analysis, would be appropriate.

3. Results and discussion

This space elevator environmental LCA quantified and evaluated the potential impacts from the production, deployment, and use of the space elevator system proposed by Swan et al. (2013). Three space elevator design configurations/business plans were presented by Swan and evaluated in this study for both cradle-to-gate and cradle-to-use scopes: *One-Tether Initial Space Elevator, Two-Tether Initial Space Elevator, Additional One-Tether Space Elevator*. The *One-Tether Initial Space Elevator* scenario was the base primary technical design configuration, while the *Two-Tether Initial Space Elevator* scenario represented the recommended business plan configuration. The *Additional One-Tether Space Elevator* scenario represented future space elevator systems deployed with a previous space elevator (without the need for initial rocket deployment). The *Additional One-Tether Space Elevator* scenario showed the lowest environmental impact, while the *Two-Tether Initial*

Table 2
Space elevator LCA primary inventory data values, units, and sources.

Inventory Data	Value	Unit	Source
Carbon Nanofiber (CNF) Production	6.30E+03	kg CNF/1-Tether	Swan et al., 2013
Benzene Production (for CNF)	4.70E+00	kg Benzene/kg CNF	Khanna et al., 2008
Hydrogen Sulfide Production (for CNF)	2.00E-01	kg H_2S/kg CNF	Khanna et al., 2008
Hydrochloric Acid Production (for CNF)	1.60E+01	kg HCl/kg CNF	Khanna et al., 2008
Hydrogen Production (for CNF)	1.72E+00	kg H_2/kg CNF	Khanna et al., 2008
Energy Production (for CNF)	2.52E+03	MJ/kg CNF	Khanna et al., 2008
Tether Design Lifespan	1.00E+01	Years/Tether	Swan et al., 2013
Space Elevator Design Lifespan	5.00E+01	Years/Space Port	Swan et al., 2013
Cost to Produce 14 Climbers (for 2 Tethers)	9.74E+08	$USD2013	Swan et al., 2013
Number of Climbers per Each Tether	7.00E+00	Climbers/1-Tether	Swan et al., 2013
Cost to Produce Space Nodes (for 2 Tethers)	9.31E+08	$USD2013	Swan et al., 2013
Cost to Produce 2 Tethers	4.55E+09	$USD2013	Swan et al., 2013
Cost of Operations Center (for 2 Tethers)	9.55E+08	$USD2013	Swan et al., 2013
Cost to Produce 2-Tether Space Elevator	1.16E+10	$USD2013	Swan et al., 2013
Cost to Launch Initial Seed Tether	7.00E+08	$USD2013	Swan et al., 2013
Operations Center Area (for 2 Tethers)	2.04E+03	m^2	Swan et al., 2013
Operations Center Height	3.00E+00	m	Estimate[a]
Operations Center Volume (for 2 Tethers)	6.13E+03	m^3	calculation
Launch Mass for Initial Tether Deployment	8.60E+04	kg	Swan et al., 2013
Annual Design Payload to Orbit per 1-Tether	5.10E+06	kg to Orbit/yr	Swan et al., 2013
Rocket Payload to GEO	4.02E+03	kg to Orbit/Launch	Spacex.com
Fuel Mass per Rocket	4.84E+05	kg fuel/Launch	SpaceLaunchReport.com
Oxidizer: Fuel Ratio (LOX:RP-1) by Mass	2.56E+00	LOX:RP-1 (by mass)	Astronautix.com
Equatorial Radius of the Earth	6.38E+03	km	Carroll et al., 2017

[a] This estimate is based on an average building story height of 3 m for calculating the building construction volume for LCI database system process input unit requirement.

Space Elevator scenario showed the lowest production cost per unit mass delivered to orbit.

A detailed comparison of process contributions to the three-primary space elevator design scenarios for the cradle-to-use scope is shown in Fig. 3, a conventional representation of LCIA results. The vertical axis was normalized to show the 1-Tether Initial Space Elevator total impact set at 100%. Each TRACI impact category showed incremental reduction in impacts from the 1-Tether Initial Space Elevator to the 2-Tether Initial Space Elevator to the Additional 1-Tether Space Elevator scenario. The producer cost impact category, however, showed the lowest cost for the Two-Tether Initial Space Elevator scenario. It was notable that all process contributions for all three-primary cradle-to-use scenarios were equal other than for initial launch deployment impact contributions (dark blue) and use/payload shipment impact contributions (brown).

Regarding the 1-Tether Space Elevator model, acidification impact potential was dominated by surface transportation to the space port and energy requirements for CNF production. Ecotoxicity, non-carcinogenic, and ozone depletion impact potentials were dominated by launch, and space node and climber production. Eutrophication potential was dominated by surface transportation, CNF energy, and anchor node production. GWP was distributed between transportation, launch, space node and climber production, and CNF energy. Carcinogenic impact potential was similar to GWP with a more significant anchor node production. Smog formation, resource depletion, and respiratory effects potentials were all mostly dominated by surface transportation, with significant portions also from anchor node production and CNF energy. The 2-Tether Space Elevator model only has reduced impact potentials from the 1-Tether model in the launch deployment system process because the second tether is deployed by the first and the launch impact is allocated 50/50 between the two tethers. The Addition Space Elevator model has no launch deployment impacts and reduced surface transport impacts because of the reduced distance to reach a second optimally located space port.

In half of the 10 TRACI impact categories, the use phase alone contributed to 40% or more to all impacts over the life-cycle. The inherently low number of space elevator ports to payload sources produces larger impacts per unit payload mass. The 5 impact categories

dominated by source-to-launch-pad-transportation are acidification, eutrophication, smog formation, resource depletion, and respiratory effects. The other 5 TRACI impact categories, i.e., ecotoxicity, global warming, ozone depletion, and both carcinogenic and non-carcinogenic human health effects, had the most significant process contribution from a combination of four different inputs, namely anchor node, climber, space node, and launch vehicle construction. All the use phase transportation impacts could be reduced by improving the transportation fuel types and energy efficiency for all payload delivered to the space elevator from its source.

The energy required for CNF production had a significant process contribution (> 10%) in acidification, eutrophication, smog formation, and respiratory effects impact categories. These could be improved by utilizing sustainable energy systems and grids for terrestrial manufacture and construction of space elevator infrastructure and components. Anchor node (offshore platform) construction had a significant process contribution (> 10%) in acidification, eutrophication, carcinogenics, smog formation, and respiratory effects. These impacts could be reduced by using sustainable engineering and design practices when optimizing the offshore platform construction for its intended purpose. Or they could be reduced by reusing and repurposing retired offshore platforms as other space elevator designs suggest [22,23]. Space node production and tether climber production both had significant process contributions (> 15% each) in ecotoxicity, global warming potential, carcinogenics, non-carcinogenics, and ozone depletion. Because these processes were EIO-LCA based, specific recommendations for reducing these impacts cannot be made. Further in-depth quantitative sustainability assessments of such spacecraft production and launch systems, processes, and products are required.

4. Capacity utilization sensitivity analysis

The 1-Tether Initial Space Elevator (100% Utilization) scenario was also compared with three alternate utilization capacity sensitivities within the cradle-to-use scope. The 90%, 50%, and 10% Utilization One-Tether Initial Space Elevator cradle-to-use cases were normalized to and compared with the 100% Utilization 1-Tether Initial Space Elevator cradle-to-use scenario (Fig. 4). The only impact category that

Table 3

Space Elevator LCA Model Input Parameters and System Processes for both Cradle-to-Gate and Cradle-to-Use System Boundary Scopes for the scenario and sensitivity analyses presented in this study. Process-LCA data were derived from ecoinvent v3.1 and is identifiable by non-$USD units. EIO-LCA data were derived from the CMU model [13] and USEIO-LCA, and is identifiable by $USD2002 in the units column. Both cradle-to-gate and cradle-to-use input data is represented for the One-Tether Initial Space Elevator, Two-Tether Initial Space Elevator, and Additional One-Tether Space Elevator scenarios, while only cradle-to-use input data is required for the 90% Utilization One-Tether Initial Space Elevator and 10% Utilization One-Tether Initial Space Elevator sensitivities. NAICS = "North American Industry Classification System," alloc. = "allocation," S = "system process," GLO = "global," RoW = "rest of world."

Unit Process	Unit	Scope (Cradle-to-)	Scenario analysis			Sensitivity analysis			ecoinvent process or NAICS Code
			One-Tether Initial Space Elevator	Two-Tether Initial Space Elevator	Additional One-Tether Space Elevator	90% Utilization One-Tether Initial Space Elevator	50% Utilization One-Tether Initial Space Elevator	10% Utilization One-Tether Initial Space Elevator	
Total Lifespan Design Payload to Orbit	Total kg to Orbit	–	2.55E+08	5.10E+08	2.55E+08	2.29E+08	2.55E+08	2.55E+07	not applicable – reference flow value
Carbon Nanofiber (CNF) Materials Production	kg CNF/kg to Orbit	Gate	3.15E+04	6.30E+04	3.15E+04	–	–	–	not applicable – system process
		Use	1.24E-04	1.24E-04	1.24E-04	1.37E-04	2.47E-04	1.24E-03	
• Benzene Production (for CNF)	kg Benzene/kg to Orbit	Gate	1.48E+05	2.96E+05	1.48E+05	–	–	–	market for benzene, alloc. default, S - GLO
		Use	5.81E-04	5.81E-04	5.81E-04	6.46E-04	1.16E-03	5.81E-03	
• Hydrogen Sulfide Production (for CNF)	kg H2S/kg to Orbit	Gate	6.30E+03	1.26E+04	6.30E+03	–	–	–	hydrogen sulfide production, alloc. default, S - RoW
		Use	2.47E-05	2.47E-05	2.47E-05	2.75E-05	4.95E-05	2.47E-04	
• Hydrochloric Acid Production (for CNF)	kg HCl/kg to Orbit	Gate	5.04E+05	1.01E+06	5.04E+05	–	–	–	hydrochloric acid production, from the reaction of hydrogen with chlorine, alloc. default, S - RoW
		Use	1.98E-03	1.98E-03	1.98E-03	2.20E-03	3.96E-03	1.98E-02	
• Hydrogen Production (for CNF)	kg H2/kg to Orbit	Gate	5.42E+04	1.08E+05	5.42E+04	–	–	–	market for hydrogen, liquid, alloc. default, S - RoW
		Use	2.13E-04	2.13E-04	2.13E-04	2.36E-04	4.25E-04	2.13E-03	
Energy Production (for CNF)	MJ/kg to Orbit	Gate	7.95E+07	1.59E+08	7.95E+07	–	–	–	electricity, high voltage, production mix, alloc. default, S - US
		Use	3.12E-01	3.12E-01	3.12E-01	3.47E-01	6.24E-01	3.12E+00	
Anchor Node (Offshore Platform) Production	Platforms/kg to Orbit	Gate	2.00E+00	4.00E+00	2.00E+00	–	–	–	offshore platform production, petroleum, alloc. default, S - GLO
		Use	7.85E-09	7.85E-09	7.85E-09	8.72E-09	1.57E-08	7.85E-08	
Operation Center Construction	m³/kg to Orbit	Gate	4.09E+03	6.13E+03	4.09E+03	–	–	–	building construction, multi-storey, alloc. default, S - RoW
		Use	1.60E-05	1.20E-05	1.60E-05	1.78E-05	3.21E-05	1.60E-04	
Climber Production	$USD2002/kg to Orbit	Gate	3.76E+08	7.52E+08	3.76E+08	–	–	–	1 USD guided missile and space vehicle manufacturing - US NAICS Code 336414
		Use	1.48E+00	1.48E+00	1.48E+00	1.64E+00	2.95E+00	1.48E+01	
Space Node Production	$USD2002/kg to Orbit	Gate	3.59E+08	7.19E+08	3.59E+08	–	–	–	1 USD guided missile and space vehicle manufacturing - US NAICS Code 336414
		Use	1.41E+00	1.41E+00	1.41E+00	1.57E+00	2.82E+00	1.41E+01	
Launch Mass for Initial Tether Deployment	kg Launch/kg to Orbit	Gate	8.60E+04	8.60E+04	8.60E+04	–	–	–	not applicable – system process
		Use	3.38E-04	1.69E-04	0.00E+00	3.75E-04	6.75E-04	3.38E-03	
• Rocket Cost for Initial Tether Deployment	$USD2002/kg to Orbit	Gate	5.40E+08	5.40E+08	5.40E+08	–	–	–	1 USD guided missile and space vehicle manufacturing - US NAICS Code 336414
		Use	2.12E+00	1.06E+00	0.00E+00	2.36E+00	4.24E+00	2.12E+01	
• Liquid Oxygen (LOX) Production for Initial Tether Deployment	kg LOX/kg to Orbit	Gate	7.45E+06	7.45E+06	0.00E+00	–	–	–	market for oxygen, liquid, alloc. default, S - RoW
		Use	2.92E-02	1.46E-02	0.00E+00	3.25E-02	5.85E-02	2.92E-01	
• Rocket-Grade Kerosene (RP-1) Production for Initial Tether Deployment	kg RP-1/kg to Orbit	Gate	2.91E+06	2.91E+06	0.00E+00	–	–	–	market for kerosene, alloc. default, S - RoW
		Use	1.14E-02	5.71E-03	0.00E+00	1.27E-02	2.28E-02	1.14E-01	
Payload Shipment to Space Elevator	t*km/kg to Orbit	Gate	–	–	–	–	–	–	transport, freight, lorry > 32 metric ton, EURO6, alloc. default, S
		Use	1.00E+01	1.00E+01	3.34E+00	1.00E+01	1.00E+01	1.00E+01	
Total Production Cost	$USD2013/kg to Orbit	Gate	8.84E+09	1.16E+10	8.14E+09	–	–	–	market for benzene, alloc. default, S - GLO
		Use	3.47E+01	2.27E+01	3.19E+01	3.85E+01	6.94E+01	3.47E+02	

Table 4
Improved Pedigree Matrix. Includes five data quality indicators: reliability, completeness, temporal correlation, geographical correlation, and technological correlation, to evaluate the uncertainty and representativeness of the model's input parameters from 1 (lowest data quality) to 5 (highest data quality) as described in matrix text [28].

Data Quality Indicators→ & Scores↓:	Reliability	Completeness	Temporal Correlation	Geographical Correlation	Technological correlation
5 (Highest Quality)	Verified data based on measurements	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations	Less than 3 years of difference to the time period of the dataset	Data from area under study	Data from enterprises, processes and materials under study
4	Verified data partly based on assumptions or non-verified data based on measurements	Representative data from > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Less than 6 years of difference to the time period of the dataset	Average data from larger area in which the area under study is included	Data from processes and materials under study (i.e. identical technology) but from different enterprises
3	Non-verified data partly based on qualified estimates	Representative data from only some sites (<<50%) relevant for the market considered or > 50% of sites but from shorter periods	Less than 10 years of difference to the time period of the dataset	Data from area with similar production conditions	Data from processes and materials under study but from different technology
2	Qualified estimate (e.g. by industrial expert)	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Less than 15 years of difference to the time period of the dataset	Data from area with slightly similar production conditions	Data on related processes or materials
1 (Lowest Quality)	Non-qualified estimate	Representativeness unknown or data from a small number of sites and from shorter periods	Age of data unknown or more than 15 years of difference to the time period of the dataset	Data from unknown or distinctly different area	Data on related processes on laboratory scale or from different technology

showed an expected response to the decreased capacity utilization scenarios was producer cost, i.e. a tenfold decrease in capacity utilization caused a tenfold increase in producer cost per kg to orbit. All other impacts showed a less than 1:1 correlation to reduction in utilization, i.e. less than tenfold increase (< 1000%) in impact potential per tenfold decrease in utilization (i.e. 10% utilization scenario). Ecotoxicity, carcinogenics, non-carcinogenics, and ozone depletion impact categories all showed between an eightfold (800%) and tenfold (1000%) increased response to the tenfold decrease in utilization. Smog formation, resource depletion, and respiratory effects impact categories showed less than a fivefold (< 500%) response to the tenfold utilization decrease.

The expected increase in cradle-to-use impacts from a given percent utilization was seen in the producer cost impact (i.e. expected producer cost % increase @ 50% utilization = $50\%^{-1}$ = 200%: @ 100% utilization = \$34.68/kg to GEO → @ 50% utilization = 2 * \$34.68/kg to GEO = 69.37/kg to GEO). This suggested even at 10% utilization, the cost per kilogram to GEO at \$346.84 would remain far below 2018 rocket launch costs to orbit. Given the projected consumer price for space elevator transport at \$500/kg to GEO, the possible profits range from \$153.16 to \$461.46/kg to GEO. The estimated annual profits then range from \$78 million to \$4.9 trillion per year between the space elevator scenarios evaluated in this LCA.

Every other impact category besides producer cost showed an average power increase of −0.8 (ranging between −0.55 and 0.95), meaning that the environmental impact increase from reduced utilization is less than expected (i.e. a power increase of −1). For example, GWP showed a −0.74 power function increase as utilization decreased (expected GWP increase = $\%\text{utilization}^{-0.74}$; i.e. @ 100% utilization = 2.48 kg CO_2 eq/kg to GEO → @ 50% utilization = $(0.5^{-0.74})$ * 2.48 = 4.14 kg CO_2 eq/kg to GEO). These findings showed that any space elevator utilization above 50% of the design capacity would produce no more than a doubling of cradle-to-use impacts.

The pedigree matrix uncertainty analysis (Table 4) showed that the LCI data related to space vehicle production showed the greatest uncertainty, with both climber and space node production process average data quality scores of 2.8/5. The average of all scores was 3.7/5 showing a reasonable, however, lower-than-ideal level of certainty in the data and findings. This further highlights the need for future sustainability assessments of the space elevator design as well as existing orbital transportation technologies.

5. Conclusions

The LCA results showed the space elevator designs in Swan et al. (2013) to be an environmentally sustainable and economically viable option for future orbital transportation, and highlighted system elements for targeted impact reduction. These results showed that use-phase impacts could be reduced by improving the transportation systems used to deliver payloads to the space elevator port from around the globe, and by optimally placing future space elevator ports to reduce the transportation impacts for both systems. Findings also showed the potential for significant positive economic impact from the space elevator design even with capacity utilization reduced to 50% (< \$70/kg to GEO). However, because technologies required for space elevator and CNF tether production are still in development, further sustainability and LCA studies must be completed as the space elevator research, development, and design process moves forward. This study also emphasizes the need for application of sustainability engineering and quantitative sustainability assessment methodologies to the spacecraft and orbital transportation systems and industries. Spacecraft production and space industry LCI data would significantly reduce the uncertainty with such LCA results.

Table 5

Uncertainty and Representativeness of LCI Data to the Space Elevator System via the Improved Pedigree Matrix. System process averages of the five data quality indicators are provided.

Data Quality Indicators → & Processes ↓:	Reliability	Completeness	Temporal Correlation	Geographical Correlation	Technological correlation	Average
Carbon Nanofiber (CNF) Production	4	4	3	4	3	3.6
Anchor Node (Offshore Platform) Production	4	4	3	4	4	3.8
Operation Center Construction	4	4	3	3	4	3.6
Climber Production	3	3	2	4	4	3.2
Space Node Production	3	3	2	4	4	3.2
Launch Mass for Initial Tether Deployment	3	4	4	4	5	4
Rocket Cost for Initial Tether Deployment	4	4	4	4	5	4.2
Liquid Oxygen (LOX) Production for Initial Tether Deployment	4	3	4	4	5	4
Rocket-Grade Kerosene (RP-1) Production for Initial Tether Deployment	4	3	4	4	5	4
Payload Shipment to Space Elevator	3	3	4	3	2	3
Total Production Cost	3	3	4	4	5	3.8
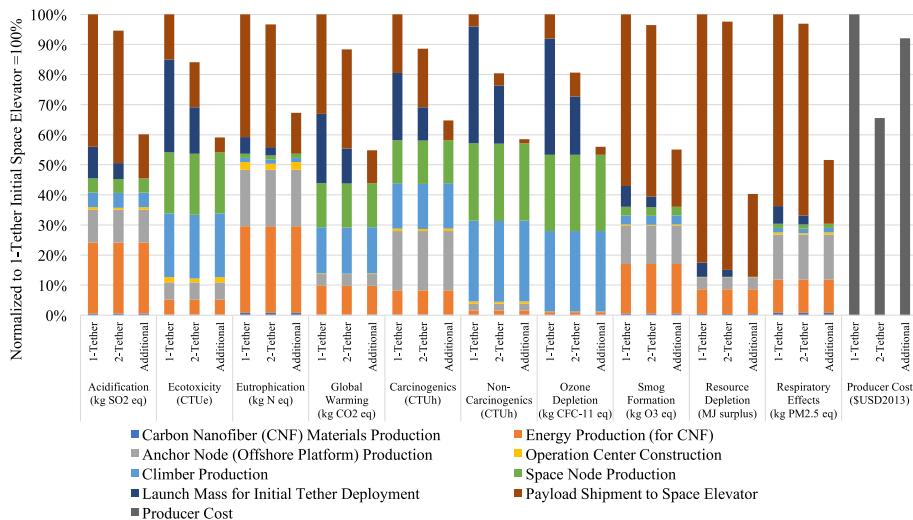
Fig. 3. Life Cycle Impact Assessment Cradle-to-Use Results for Three Primary Space Elevator Design Configurations. All three design plans modeled were based on Swan et al. (2013). Cradle-to-use system process individual contributions for each quantified impact category are illustrated for the primary design scenarios: 1-Tether Initial Space Elevator, 2-Tether Initial Space Elevator, and Additional 1-Tether Space Elevator. The vertical axis scale was set by normalizing to the 1-Tether Initial Space Elevator scenario impacts at 100%. Cost impacts were included in the figure but not itemized for each system process contribution.
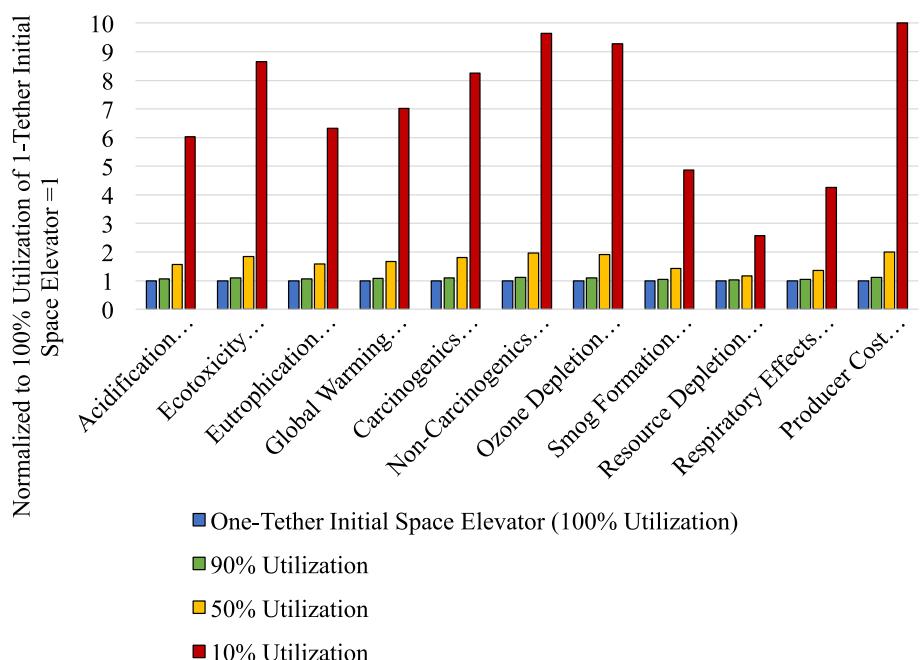

Fig. 4. Cradle-to-Use Space Elevator Capacity Utilization Sensitivity Analysis and Comparison to Space Elevator at 100% Utilization. The expected sensitivity relationship to utilization was found in the producer cost impact category.

Acknowledgements

References

[1] J. Coopersmith, The cost of reaching orbit: ground-based launch systems, Space Pol. 27 (2011) 77–80.

[2] J. Hampson, The future of space commercialization, US House Committee on Science, Space Technology, vol 25, 2017.

[3] P.A. Swan, D.I. Raitt, C.W. Swan, R.E. Penny, J.M. Knapman, Space Elevators: an Assessment of the Technological Feasibility and the Way Forward, International Academy of Astronautics, Virginia, 2013.

[4] N.M. Pugno, Towards the Artsutanov's dream of the space elevator: the ultimate design of a 35GPa strong tether thanks to graphene, Acta Astronaut. 82 (2013) 221–224.

[5] D. Raitt, Space Elevators: A History: A History, Lulu. com, 2017.

[6] D.I. Raitt, A historical look at the concept of space elevators, New Space 3 (2015) 231–238.

[7] J.M. Knapman, P.A. Swan, The status of space elevator infrastructures, New Space 3 (2015) 219–230.

[8] V. Khanna, B.R. Bakshi, L.J. Lee, Carbon nanofiber production, J. Ind. Ecol. 12 (2008) 394–410.

[9] ISO, ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework, ISO - International Organization for Standardization, 2006.

[10] ISO, ISO 14044:2006 Environmental management – Life cycle assessment – Requirements and guidelines, ISO - International Organization for Standardization, 2006.

[11] S.O. Shrake, M.M. Bilec, A.E. Landis, The application of a multi-faceted approach for evaluating and improving the life cycle environmental performance of service industries, J. Clean. Prod. 42 (2013) 263–276.

[12] K. Simonen, Life Cycle Assessment, Routledge, 2014.

[13] CMU, Economic input-output life cycle assessment (EIO-LCA) model, Carnegie Mellon Green Design Initiative, Pittsburgh, 2002.

[14] FAA, The annual compendium of commercial space transportation: 2018, FAA Office of Commercial Space Transportation Washington, DC, 2018.

[15] B.W. Carroll, D.A. Ostlie, An Introduction to Modern Astrophysics, Cambridge University Press, 2017.

[16] C.W. Swan, Introduction to space elevators and new space, New Space 3 (2015) 211–212.

[17] C.W. Swan, P.A. Swan, Why we need a space elevator, Space Pol. 22 (2006) 86–91.

[18] C.W. Swan, P.A. Swan, J.M. Knapman, D.I. Raitt, The future: space elevators seem feasible, New Space 3 (2015) 239–240.

[19] P.A. Swan, Opening up earth–moon enterprise with a space elevator, New Space 3 (2015) 213–217.

[20] D. Raitt, B. Edwards, The space elevator: economics and applications, Proc. of the 55th Int. Astronautical Congress-Vancouver, Canada, 2004.

[21] D. Raitt, P. Gyger, A. Woods, Innovative Technologies from Science Fiction for Space Applications, ESA Publications Division, 2001.

[22] B.C. Edwards, Design and deployment of a space elevator, Acta Astronaut. 47 (2000) 735–744.

[23] B.C. Edwards, E.A. Westling, The Space Elevator, BC Edwards, 2003.

[24] M.Z. Hauschild, R.K. Rosenbaum, S.I. Olsen, Life Cycle Assessment: Theory and Practice, Springer, 2017.

[25] J. Bare, TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0, Clean Technol. Environ. Policy 13 (2011) 687–696.

[26] J.C. Bare, P. Hofstetter, D.W. Pennington, H.A.U. De Haes, Midpoints versus end-points: the sacrifices and benefits, Int. J. Life Cycle Assess. 5 (2000) 319–326.

[27] T.W. Bank, World development inidcators, World Development Inidcators, 2008 https://data.worldbank.org/.

[28] B.P. Weidema, C. Bauer, R. Hischier, C. Mutel, T. Nemecek, J. Reinhard, C. Vadenbo, G. Wernet, Overview and methodology: data quality guideline for the ecoinvent database version 3, Swiss Centre for Life Cycle Inventories, 2013.