Sustainability in a Commercial Space Race

A Research Paper Submitted to the Department of Engineering and Society

Presented to the Faculty of the School of Engineering and Applied Science

University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree

Bachelor of Science, School of Engineering

Marc Brightwell

Spring 2024

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Advisors

William F. Stafford, Jr., Department of Engineering and Society

Introduction

One of the most fascinating and technically challenging achievements in human history is the conquest of space. Amongst the underlying rigor of spaceflight resides its inherently energy-intensive nature. Each mission or venture to locations outside this planet's atmosphere comes at the expense of abundant resources and a notable impression on the environment. Simply, human spaceflight is responsible for the emissions of gasses and particles that affect the composition and temperature of the atmosphere from the surface to the upper atmosphere, where objects are in orbit (Ross, 2022). Every layer of Earth's atmosphere is exposed to harmful emissions through combustion products expelled from a rocket's engine during flight. Aerosol emissions from spacecraft have played an increasing role in the aerosol population housed within the stratosphere. The international space sector is responsible for emitting black carbon particles that accumulate in the stratosphere, absorb solar radiation, and subsequently warm the surrounding air (Maloney, 2022). These emissions have led to more significant issues, including overall stratospheric heating and ozone depletion. These climate responses scale in an almost linear fashion with an increase in rocket emissions. The prolonged established presence of humans in space has also given way to a mounting collection of debris in Earth's orbit. Millions of pieces of space junk that reside in orbit have been shown to have destabilizing effects on the space environment and represent an issue of spaceflight that will inevitably grow without proper mitigation. In summary, rocket launches leave carbon imprints, produce substances that deplete the ozone layer, and may leave debris in space and our atmosphere (Wishwakarma, 2023). The global impacts of spaceflight have long been viewed as limited in scope, but this notion is no longer applicable with the advent of the commercial industry.

Paper Overview

As we prepare for a new era of space exploration primarily conducted by the private sector, an essential socio-technical question emerges: How can we maintain and advance sustainability amid increased space exploration brought on by privatization and commercialization? This first section of this paper explores the relevant details of privatization within the space industry and the environmental implications that have grown in scale. The second section will review the STS framework and research methods used during this investigation. Further along, the third section will review and analyze the private spaceflight company SpaceX for the purpose of the case study. Lastly, the report will conclude with an overview of key findings followed by a discussion of recommendations and potential solutions.

Context for Privatization and Increase in Spaceflight

Growth of the Private Sector

The shift of space exploration towards privatization has led to an inevitable increase in launches happening every year by various commercial entities, and the overall trend has shown no indication of slowing down. Instead of a single government-backed agency like NASA serving as the sole actor within the space sector, multiple billionaire-backed companies have arisen in the last decade or so that have now comprised most of the industry today. The turn toward space commerce, as demonstrated by organizations like SpaceX, Blue Origin, and others, signifies a dramatic change in the environment surrounding space exploration (Genta, 2014). This change brings with it several environmental issues in addition to speeding up innovation and cutting costs. Nevertheless, a connection between the government and the political facets of space exploration still exists that must also be addressed.

Environmental Ramifications of Increased Privatization

The implications of increased private launches for the environment emphasize how crucial the issue of sustainability has become. Launching vehicles into space has always been an endeavor of a grand scale. Leaving this planet's atmosphere requires a significant amount of thrust, which in turn requires a considerable amount of fuel. Emissions from commonly used solid and liquid-fueled propellants have undoubtedly left an impression on the environment. These motors used within space launch vehicles have been directly linked to stratospheric ozone depletion (Dallas, 2020). Not to mention, valuable resources are also put into constructing infrastructure and hardware used in spaceflight. Additionally, the longstanding issue of mounting space debris has only been exacerbated by the global increase in launches, with a solution in long-term management becoming essential. This growing issue of space debris, considerable amounts of ozone layer depletion, and the increasing carbon footprint of rocket launches are all signs of a rapidly expanding industry surpassing the systems intended to sustain it.

STS Framework for Analysis and Research Methods

STS Framework

The Actor-Network Theory (ANT) will be used in this study to better understand the intricate relationships between the many parties involved in the commercial space sector. Originally developed in the 1980s, the Actor-Network Theory is a sociology theory used to relate human and non-human entities within a single network. It is an analysis of association among these actors within the network, emphasizing aspects of power, politics, and space (Muller, 2015). This STS research intends to use the Actor-Network Theory to investigate the multi-faceted landscape of commercial spaceflight and how each actor or association may lend itself toward the goal of sustainable development. In this instance, relevant actors would include

corporations, governments, international organizations, environmental groups, and the technology itself. Moreover, this research aims to shed light on the current issues and suggest strategies for a more sustainable interaction with the final frontier.

Research methods

A multimodal approach involving scientific journals, literature reviews, and environmental impact data analysis will be used to analyze the dynamic of sustainability within the commercial sector of the space industry. The study will look at past data to track the development of commercial space activities and their effects on the environment, as well as present laws and industry norms on both the international and domestic levels. It will also investigate new technological developments and potential legislation meant to allay these worries. The goal of the research is to create a comprehensive illustration of the current status of sustainability in commercial space exploration by gathering and combining information from various sources, followed by an analysis of how we should work to mitigate issues pertaining to the environment.

Case Study

The Emergence of a Commercial Giant

Founded in 2002, SpaceX is an American aerospace company that has grown into one of the leaders in the commercial spaceflight industry. The company's main objective has primarily been to make spaceflight affordable. SpaceX was the first private company to successfully launch a spacecraft into Earth's orbit and successfully return it.

Over the years, SpaceX has shown to have a considerable footprint within the global space economy. As previously mentioned, SpaceX is one of the biggest pricing competitors, given how driven the company's mission has been regarding the affordability of spaceflight. This

increase in affordability has essentially broadened the horizon of potential customers. It has made spaceflight accessible to individuals and groups that would not have been able to afford it with traditional technology. Moreover, this increase in operational efficiency has only further driven the overall launch frequency for the organization, further establishing its commanding presence within the market. Not to mention, SpaceX has engaged in a myriad of commercial and governmental partnerships that have been essential in developing their missions.

The private sector's prevalence within the industry directly corresponds to SpaceX's evolution as a company. For instance, comparing 2020 with 2023, SpaceX has more than doubled the number of launches within a year. More specifically, SpaceX had 26 launches in 2020 and 98 launches in 2023.

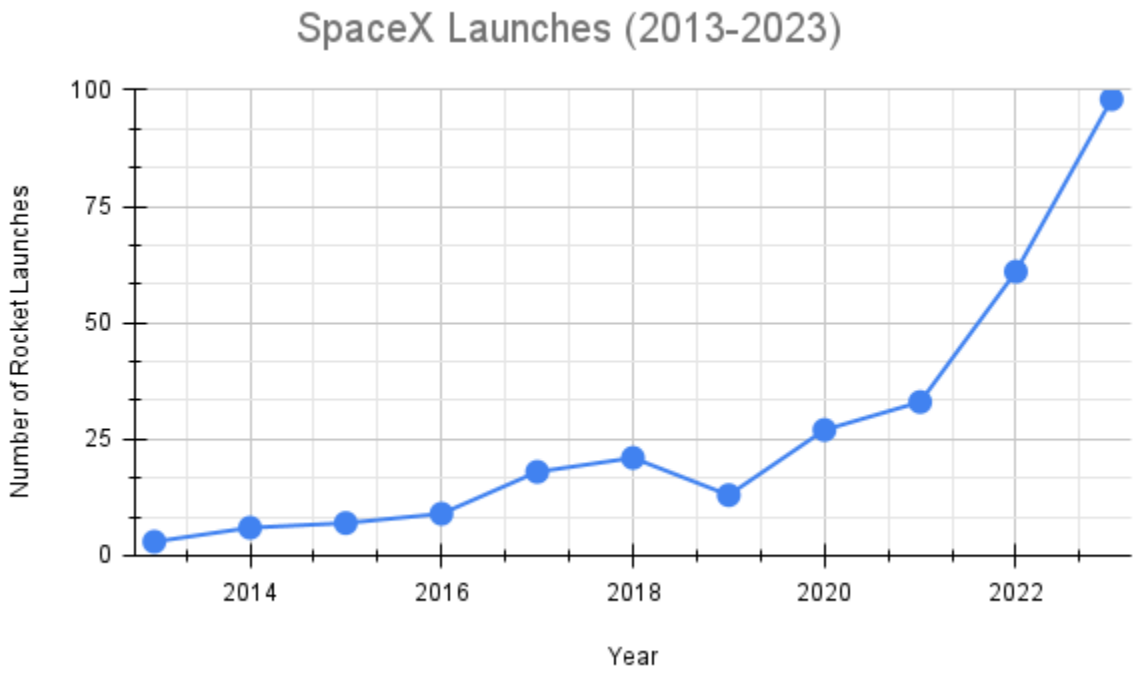

Figure 1. Total SpaceX launches year-by-year from 2013 to 2023

One of the main driving forces behind the increased frequency of launches is the commercial demand for satellite deployments. As mentioned earlier, SpaceX's development in

the area of affordability has made its services accessible to a relatively larger client base. The company also actively partners with the government to execute periodic resupply missions to the International Space Station. In addition, the company has made a commitment towards the colonization of Mars, which has further driven it to maintain a persistent presence with launches and various testing that will contribute to this goal.

Existing Efforts in Sustainability

A byproduct of the company's efforts in affordable spaceflight has been development within efficiency and sustainability. For instance, the company has developed technology with an unprecedented degree of reusability for launch vehicles. SpaceX has claimed its latest model of the Falcon platform is capable of ten launches without major refurbishment (Miraux, 2022). This approach of reusability is imperative when discussing the potential mitigation of growing space debris. By applying the simple principle of reuse, SpaceX was able to reduce the cost of launch to high orbit by over $6,000 per kilogram while reducing environmental impact potential averages by >40% below the Falcon 9 system (Harris, 2019). Similarly, Starship, another of their primary launch vehicles, also implements first-stage reusability that bolsters relatively high cost efficiency compared to past technologies. Starship is the spacecraft that will serve as transportation for the future missions to Mars. The company has designed the engines to consume fuel that will also be available on Mars, taking advantage of the red planet for its resources.

STS Framework Analysis

For this specific case concerning a private spaceflight organization, a handful of actors should be considered when discussing the dynamics within commercial space exploration. More specifically, the actors to be considered in this instance are competition, regulatory bodies, clients, investors, technology/infrastructure, the scientific community, and the organization itself. The competition for this case represents other private spaceflight companies and organizations that SpaceX competes against regarding market share and awarded contracts. The main competition against SpaceX is comprised of Blue Origin, United Launch Alliance, and Boeing. For regulatory bodies, these are the organizations that set standards and establish regulations with which SpaceX must comply. The primary regulatory bodies that should be considered are the Federal Aviation Administration, the United Nations, and the U.S. government. Regarding clients, these are organizations or individuals that SpaceX directly works with or provides services for. Besides the various private organizations that make up the clientele for the organization, the primary entity that enlists the services of SpaceX is the U.S. government in the form of major multi-billion dollar contracts from the Air Force or, in most instances, NASA. Technology and infrastructure are other notable factors to consider when doing a comprehensive evaluation. More specifically, the leading technologies to consider are the company's primary launch vehicles: the Falcon 9, the Falcon 9 Heavy, and the Starship. Furthermore, propellant technology is an imperative consideration concerning the relevant technological aspects. Pertaining to the scientific community, this primarily represents the various organizations and institutions conducting research and development in fields that directly relate to technology within spaceflight. Lastly, two major actors integral to the network are the investors within the organization and the organization itself.

Results

Overview of Analysis

Through analysis with the STS framework, it's evident that there are certain associative and inter-relational developments within the commercial space sector that would not only facilitate the advancement of sustainability but, in certain instances, directly clear the way for a more sustainable future. Starting with the organization itself along with the inclusion of investors, an establishment of some form of a board of ethics would provide oversight within the company and would lend itself towards sustainable practices. Moreover, the organization could consider the implementation of marketing that conveys environmentally sound practices and, in a way, sell the notion of sustainability as a competitive edge within the industry.

Another aspect worthy of consideration is the nature of competition within the commercial sector of spaceflight and the generally positive residual effects competition has towards cultivating sustainability across the entire industry. All commercial spaceflight companies garner revenue from clientele through the services they provide, but a significant amount of money is also gained through winning large government dealt contracts. As mentioned, NASA has become one of the primary clients for commercial spaceflight. The nature of NASA's presence within the space industry has drastically changed over the last few decades. NASA's role has evolved from being the primary executor of spacefaring missions to being more of a facilitating entity in partnership with various private companies.

Moreover, this decentralization of development to a multi-company-based industry has organically become a driver of innovation and efficiency. These entities that award major contracts strongly consider cost efficiency when considering whom they give the contract to. Furthermore, this consideration directly incentivizes companies to develop cost-efficient

technology, which coincides with sustainable technology and infrastructure. These advancements in efficiency from the private sector have also proven to be leaps and bounds ahead of the efficiency of government-developed technologies in the past. This notion is evident with the development of the Falcon 9, a rocket developed by SpaceX. NASA expressed how the 400 million dollar price tag that was attached to the development of the Falcon 9 was a mere ten percent of the cost of a rocket that was developed using traditional government contracting (Seedhouse, 2022). All that being said, SpaceX has become such a dominant presence within the commercial market that the effect of competition on motivating innovation has presumably become slightly diluted. In 2020, SpaceX was responsible for approximately two-thirds of NASA's launches (Yuree, 2023).

Equally important, the regulatory bodies governing spaceflight certainly bolster considerable influence across the entire industry. The FAA, through the Office of Commercial Space Transportation (AST), was established to ensure the compliance of U.S.-based entities with international obligations concerning spaceflight. The AST" licenses commercial launch and reentry vehicles and commercial spaceports." However, recent regulatory reform in the FAA/AST licensing process has given" launch companies the flexibility to propose alternative ways to meet safety requirements". This shift in regulation is a direct representation of the commercial spaceflight industry moving in the wrong direction of looser environmental review processes (Simpson, 2022); instead of simply integrating more streamlined regulation, a more balanced regulatory approach that includes performance-oriented standards while also maintaining a sufficiently diligent environmental review process.

Lastly, relevant discussion concerning sustainability can be found within the nature and relation amongst the organization, the technology, and the scientific community as a whole. To

begin with, SpaceX has shown relatively great strides toward efficiency compared to other competitors within the industry. Most importantly, the company's advancements in reusability have dramatically cut back costs while minimizing overall resource usage. Nevertheless, most SpaceX launches have rockets powered by engines with super-refined kerosene as the main combustion component (Lee, 2019). A significant byproduct of kerosene is black carbon, which, as mentioned earlier, is a significant source of radiative forcing, subsequently leading to a detrimental heating effect within the atmosphere (Ross, 2014).

Moreover, the nature of SpaceX's research and development is an important consideration. SpaceX is a highly vertically integrated company that produces over 90% of its rocket parts in-house. In relating this to the scientific community, a myriad of institutions and aerospace research organizations represent potential partnerships in innovation and sustainable development.

Key Findings

Unsurprisingly, one of the primary aspects of this research topic was the current state of international and domestic commercial spaceflight regulation. The Outer Space Treaty of 1967 represents the most significant form of legislation on an international level. The relatively archaic nature of this treaty is conveyed through its omission of any discussion on private actors or environmental issues in spaceflight, having been drawn up during the earlier stages of space exploration. Domestically, the National Environmental Policy Act is one of the very limited environmental statutes in the U.S. that regulates rocket launches by requiring environmental values to be incorporated into the decision-making process. However, the NEPA and FAA are primarily ineffective at regulating the entire environmental effect of spaceflight due to the

relatively low threshold private companies must meet to be considered adequate for their environmental assessments (Yuree, 2023).

The critical points in reducing the carbon footprint from launches are all technology-driven. This is a problem that will be largely remedied through the use of innovative propulsion systems that use less polluting fuel. The challenge is that all current propulsion systems utilized by major companies and propellent types simply are not eco-friendly. Everything considered, there have still been advancements in greener propellant technology on a smaller scale that may hopefully have a larger presence within the industry down the line. These propellants consist of chemicals with lower toxicity while still boasting the necessary specific impulse for missions in the future. Notably, the Green Propellant Infusion Mission (GPIM) recently demonstrated a high-performance, non-toxic green monopropellant (McLean, 2020).

Recommendations and Solutions

Technology

From a technological perspective, companies must continue or enhance their research and development efforts in reusable launch vehicles. The implementation of reusability has shown to be not only an increase in cost efficiency for a company but also a method of significantly limiting the amount of material that is left over from spaceflight. Moreover, reusability is a direct route towards limiting the overall resource consumption with spacefaring endeavors. Similarly, there needs to be further investment from industry leaders like SpaceX in the research and development of greener propellant technologies.

Policy

The current state of policy and regulation within commercial spaceflight warrants several changes. Firstly, the United Nations should develop a new international space treaty

encompassing the current landscape of spaceflight, with specific articles concerning private actors within the industry. Equally important, a new treaty must establish a framework with environmental considerations. Moving onto domestic regulation, the FAA and NEPA need to re-establish a slightly greater sense of rigidity concerning safety and environmental assessments, limiting private companies' alternatives to meet safety requirements. Even further, regulatory and governing agencies need to consider providing incentives to private companies that bolster minimal impact assessments in the form of a monetary reward.

Research, Development, and Partnership

In addition, commercial spaceflight companies need to strive towards being more proactive in forging partnerships within the scientific community with established institutions and organizations that have the potential to be instrumental in the development of innovation. This recommendation is especially imperative to highly vertically integrated organizations within the space sector that limit their scope of potential development by keeping to themselves and choosing to do the majority of development strictly in-house.

Connection with Literature

Similar sentiments regarding the need for an overhaul in regulation are present in *One Way Ticket to Mars* (2023), which mentions further establishing domestic and international regulation. The journal further recommends involving more regulatory bodies at the domestic level, using the Civil Aviation Authority as the suggested agency. In like manner, in *Bracing for the Impending Rocket Revolution*, the journal also details the inadequacy of current regulation and reiterates the idea of private actors being omitted in the majority of the current regulatory framework.

Conclusion

It is essential to consider how society may preserve sustainability in an environment of increased space endeavors due to the privatization and commercialization of the space sector. Spaceflight is an inherently energy-intensive process that seemingly limits the potential avenues of sustainability and, coupled with the prevalence of private launches and exploration, presents substantial environmental implications. Nevertheless, there are routes we must take and technologies we must further invest in that can minimize the resource-depleting nature of human space exploration. More specifically, the space industry must continue developing the reusability of launch vehicles, along with further exploration of green propellant technologies. Beyond the technological aspects, governing bodies worldwide need to commit to a comprehensive international and domestic policy that properly encompasses the objective of minimizing environmental impact. Moreover, actors within the private spaceflight sector need to be more geared towards developing partnerships for collective innovation towards a more sustainable future. We must maintain and continue to promote a sustainable approach when navigating a field with the potential of notable impact on our environment. The quantity and scope of private space initiatives raise the significance of these issues, further necessitating a discussion of sustainable solutions.

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