# Exploring the Environmental and Socio-technical Impacts of Space Launch Vehicles

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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

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# STS Research Paper

## Introduction

The scope and frequency of rocket launch vehicles and sounding rockets continue to expand rapidly, and that outcome has significantly impacted societies and environments. This paper aims to explore how different stakeholders perceive the costs and benefits of social, environmental, and economic factors of rocket launches. That is important because private industries and governments heavily rely on small suborbital or larger interplanetary rockets for a vast range of missions. Rockets enable access to Earth's orbit and empower planetary sciences, military applications, surveillance, the internet and communication, academic research, and the exploration of the solar system. Rocket launches continue to become less expensive and more accessible. Therefore, their socio-technical and environmental impacts are becoming more prominent.

Investments in rocket activity have promoted numerous advances in science and technology. The technology and knowledge involved with designing, making, and launching sounding rockets often translate to many other aerospace applications; furthermore, the spinoff technologies of rocketry trickle down to many non-aerospace industries, such as healthcare, internet and communications, and environmental sciences (NASA, n.d.). Rockets facilitate access to space and allow scientists, researchers, and even students to study the Earth, its atmosphere, and outer space. Furthermore, rocketry creates thousands of job opportunities through all that investment and promotes vast economic development (Baum, 2009). Furthermore, advances in space exploration are often closely tied to national pride and a country's status on the global technology stage. Nonetheless, in addition to those benefits, this

paper shows that rockets have notable harmful consequences for the atmosphere, natural ecosystems, and our planet's health.

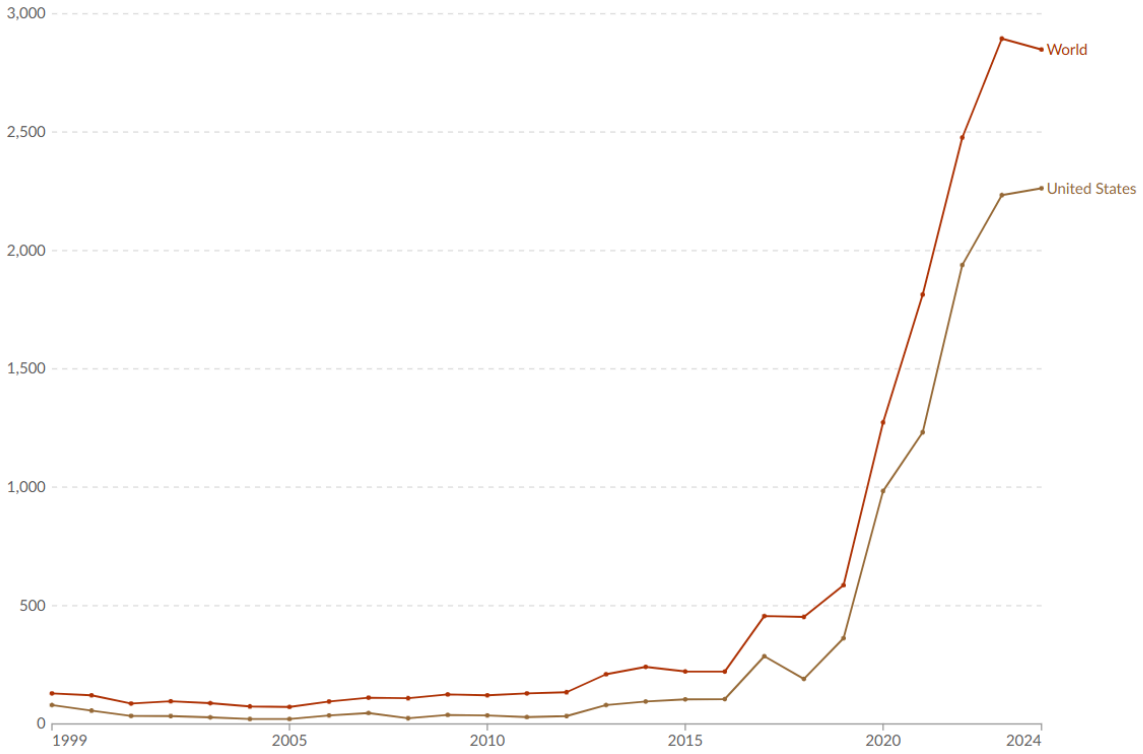
Rockets use powerful motors or engines to fulfill their demanding mission requirements. Therefore, they have notable adverse environmental consequences. For example, rockets often burn complex hydrocarbon fuels and emit significant pollution, including greenhouse gasses, nitric oxides, and harmful particulate matter (Donou-Adonsou et al., 2024). Those pollutants are responsible for health concerns and respiratory illnesses, including asthma, decreased lung function, and "premature death in people with heart or lung disease" (Health and Environmental Effects, n.d.). The greenhouse gas emissions from rocket launches are partially responsible for rises in global temperatures, which lead to numerous environmental challenges, including extreme weather, rising sea levels, ocean acidification, and biodiversity loss. Additionally, extreme noise levels and sonic booms from rockets have raised concerns about the impact of noise pollution on the wildlife and ecosystems surrounding launch pads (Kuthunur, 2023). When spacecraft or rocket booster sections re-enter the atmosphere and land, in SpaceX's case, they create sonic booms. Those shockwaves, along with the rumbles from rocket launches, startle wildlife.

With the private space sector's recent advancements, the frequency of rocket launches has rapidly increased in recent years. SpaceX is a major actor in the space industry and plans to launch Starship, their flagship launch vehicle, 25 times in 2025, a drastic increase from only five permitted launches in 2024 (Kelly, 2024). That explosive trend in launch frequency is consistent throughout the space industry as access to space expands. Figure 1 shows that the number of global objects launched into space early increased by six times in only the past 5 years. Given

those trends, it is imperative to research rocket launch's social, environmental, and technical impacts.

**Figure 1**

*Annual Number Of Objects Launched Into Space By The World And The United States From 1999 To 2024*




Note. From "Annual number of objects launched into space," 2025, Our World in Data

**Background and Significance**

Societies and individuals significantly rely on the direct and indirect services space launch vehicles provide. Rocket launches benefit stakeholders directly and indirectly via spinoff technologies. For example, rocket launches support missions that empower the internet, global communication, GPS, weather forecasting, national security, and exploring the Moon and Mars. Therefore, individual stakeholders benefit from those applications of space launch systems.

Furthermore, innovation in launch systems often leads to numerous spinoff technologies that impact fields like healthcare, recreation, transportation, and other commercial applications (NASA, n.d.).

Studying rocket activity's socio-technical and environmental trade space is more relevant today than ever. With the growing influence of private space companies, rocket launches are becoming more frequent. Some notable private space launch companies include SpaceX, Blue Origin, Boeing, Sierra Space, Scaled Composites, Firefly Aerospace, Relativity Space, and Stoke Space. These companies have varying business stability, experience, and launch readiness levels. SpaceX, in particular, has revolutionized access to space. With the development of their Falcon Nine rocket, access to low Earth Orbit is becoming cheaper and easier. For comparison, the cost of payload carried by the Falcon 9 rocket is about $2,720 per kilogram; while it used to cost $54,500 per kilogram of payload to be carried by the space shuttle (Jones, 2018). Furthermore, SpaceX predicts that with the advancements of the Super Heavy Starship, which is currently in development, it can send a kilogram of payload to space for only about $150 (Wang, 2024).

That impressive promise is partly due to the reusability of Starship. Elon Musk envisions a near future where rockets are completely reusable and rapidly deployable. Although that ambitious goal contradicts today's tradition of single-use rockets, it is a fast-approaching aerospace standard. To appreciate the benefit of reusable rockets, it is worthwhile to imagine a scenario in the context of planes and commercial aviation. Imagine a scenario where passengers board a single-use plane from New York to Los Angeles, unboard the plane, and watch as airport employees destroy the aircraft. Similarly, reusable rockets can reduce the environmental burden of space missions. However, reusability and reduced operations costs will increase the frequency of rocket launches, which may harm the environment.

Given the rapidly growing field of private space flight, there is a gap in research on the impact of privatization on the environmental sustainability of rocket launches. Therefore, current policies are inappropriate for protecting the environment from the negative risks and consequences of space launches. For example, a Time article explains how numerous environmental groups like the Center for Biological Diversity, the American Bird Conservancy, and the Surfrider Foundation filed suit against the FAA for its role in licensing the inaugural launch of SpaceX's Starship launch vehicle (Kluger, 2023). Starship exploded during that inaugural launch, and the environmental groups argued that the FAA failed to rigorously assess and mitigate the environmental impact of Starship's launch. Furthermore, Loubert et. al. explain that policy development is lagging behind the pace of innovation in the private space sector (2024). Therefore, studying the socio-technical and environmental tradespace is important to inform policies and regulations to protect the environment and promote advances in space launch technologies.

**Methodology**

This paper will explore the relevant literature that presents stakeholder perspectives to understand better the trade-offs between the environmental and socio-technical implications of growing investments in rocket activity. The reviewed literature includes books, journal articles, news articles, and online opinion pieces. Sources primarily originate from the United States, but some international articles were also reviewed. This discussion expands on the current literature by applying the Social Construction of Technology (SCOT) framework in conjunction with a broad cost-benefit analysis paradigm.

SCOT is an evaluative framework first introduced by Wiebe Bijker and Trevor Pinch. In their 2012 book, Bijker and Pinch explain that technologies have interpretative flexibility according to SCOT. SCOT emphasizes the non-linearity of technologies and explains that relevant social groups interpret or modify a technology differently according to their needs and objectives. The authors explain that power dynamics and wider socio-cultural politics often drive the dominant interpretation of a given technology. SCOT is a useful framework for exploring the socio-technical implications of rocket launches because it places relevant social groups at the center of analysis. Therefore, SCOT is appropriate for understanding the diverse perspectives on rocket activity.

In addition to SCOT, this paper adopts ideas from the cost-benefit paradigm to assess the impact of rocket launches on different stakeholders. While many sources in the literature analyze social, technical, economic, and environmental considerations of rocket launches independently, this paper explores many of those elements together. Therefore, when applying the cost-benefit paradigm, this discussion differs from some of the literature in how it defines standing – or "whose costs and benefits count in CBA" (Baum, 2009). While other papers focus on a few specific stakeholders, this discussion aims to assess the impact of rocket activity on various actors, including individuals, neighborhoods, non-human organisms, ecosystems, and the environment.

It is admittedly challenging to objectively evaluate the costs and benefits of rocket launches without a simplified model or metric, especially given a large scope of analysis. Some researchers try to overcome that challenge by evaluating costs and benefits in terms of money (Baum, 2009). However, a money-centered CBA is limiting because some costs and benefits do not have clearly defined monetary values associated with them. For example, annoyance because

of noise pollution in communities neighboring a launch pad is challenging to measure through money. Furthermore, some benefits of rocket activity are naturally subjective, and different stakeholders value them differently. For example, some people may value growth in job opportunities more than advances in atmospheric sciences because of rocket launches.

Ultimately, after applying SCOT and ideas from the cost-benefit paradigm to an extensive literature review, this paper aims to offer a recommendation to policymakers to address the growing scope of private space flight and the harmful environmental consequences of space launch activities.

**Literature Review**

Throughout the literature, many scholars have studied the intersection of rocket launches and environmental sustainability. Donou-Adonsou et. al. (2024) have analyzed empirical data on CO2 and greenhouse gas emissions to support the argument that rockets hurt the environment by increasing demand for natural resources, contributing to global warming, and increasing air pollution. The paper's secondary argument is that space exploration and research facilitated by rocket launches have led to numerous advancements in technology, including solar panels, energy storage systems, and agriculture. Those advancements help to mitigate the effect of climate change. Also, the source explains that rockets benefit society by advancing healthcare and transportation technologies, creating job opportunities, and supporting the economy.

Furthermore, Monte and Scatteia (2017) provide an independent assessment of the socioeconomic impact of space launch systems. Their paper provides evidence to enable the European Space Agency and other regulating bodies to decide whether to continue investing in launch capabilities. This study explores launch vehicles' economic and social impact by studying space activities' GDP impact on European countries to make that assessment. It primarily argued

that investments in aerospace companies have positive economic effects widely across non-aerospace companies.

Furthermore, researchers have studied other potentially harmful effects of rocket launches. For example, Framond and Brumm have studied the "long-term effects of noise pollution on the avian dawn chorus" (2022). Framond and Brumm studied birdsongs around the Berlin Tegel airport before and after the airport closed down. Before the closure, they found that because of air traffic noise pollution, birds started singing earlier in the morning to have more uninterrupted singing time. However, after the airport closed, some birds returned to their original singing time while others stuck with their earlier singing adaptation. Their study shows that long-term noise pollution has a lasting impact on wildlife and their ecosystem, and there is more to learn about the impact of noise pollution.

Other scholars have recognized the harmful effects of rockets and the challenges with an eco-friendly rocket design. For example, Musso et. al. provide details about an optimization framework for designing sounding rockets with minimal global warming potential and maximum altitude (2024). The authors use that framework to design three rockets to demonstrate the efficacy of their approach and communicate their results. The authors argue that sounding rockets are harmful to the planet because they contribute greenhouse gasses to the atmosphere and contribute to global warming. Furthermore, this source integrates the environmental and societal implications of sounding rockets with their technical considerations to provide a potential solution for this socio-technical issue.

Furthermore, Baum studies another evaluative framework to study the topic of rocket sustainability (2009). This article discusses the implementation and implications of the cost-benefit analysis (CBA) paradigm. Although the source does not hold a particular

perspective on the merits or drawbacks of sounding rockets, it provides numerous tools for evaluating their costs and benefits. For example, it uses other scholarly articles and specific examples to define possible costs and benefits of space exploration. Furthermore, this source indirectly introduces a secondary argument that could be used to support investment in space exploration and rocket technology. It expands on Monte and Scatteia's 2017 article and explains that the benefits of spaceflight and rocket launches are not only tied to their economic impact. For example, space exploration creates a sense of wonder in kids, encouraging them to pursue and advance science.

**Results and Discussion**

Reviewing the relevant literature on the costs and benefits of rocket launches reveals there is no objective argument for or against investing in rocket launch infrastructure. Rocket launches are not inherently "good" or "bad"; their impact and value depend on how different groups view and experience them. Therefore, arguing for or against investing in rocket launch infrastructure is not productive. Instead, it is more important to understand how different stakeholders interpret rocket launch technologies. This study's literature review revealed that three of the relevant stakeholders for rocket launches are environmentalists, academics, and municipalities, which include both government officials and local citizens. Although any positive or negative opinion about rocket launches is not exclusive to a specific stakeholder, the three social groups mentioned in this paper's literature review hold the following sweeping perspectives. Environmentalists argue that air and noise pollution from rocket launches have negative consequences for the planet's health. Academics may argue that advances from investing in rocket launch infrastructure lead to numerous spinoff technologies like solar panels and battery storage systems that indirectly benefit the environment. Lastly, municipalities point

to the economic development caused by investment in rocket launch infrastructure as a benefit of rocket activity.

Across the board, environmentalists agree that rocket launches have a direct negative impact on the planet's health. Rockets burn significant amounts of fossil fuels to produce thrust and reach high altitudes. According to Donou-Adonsou et. al., the CO2 produced by rockets hurts the environment by increasing the demand for natural resources and creating air pollution (2024). Many rockets burn Rocket Propellant 1, or RP-1, which is a popular rocket fuel because it is stable at room temperature, relatively cheap, powerful, and not dangerously explosive (Piesing, 2022). RP-1 releases CO2, nitrogen oxides, and particulate matter like soot (Donou-Adonsou et al., 2024). These pollutants have multiple devastating impacts on the environment and human health (Health and Environmental Effects, n.d.). For example, because rockets release pollutants up through the mesosphere, unlike general aviation planes, pollution from rockets has significant global warming potential (Piesing, 2022). Furthermore, those pollutants threaten to deplete the ozone layer and negatively affect human health (Piesing, 2022). For example, particulate matter like soot is known to cause various respiratory diseases and cardiovascular diseases (Health and Environmental Effects, n.d.). Moreover, all of these negative environmental and health consequences of rocket propulsion are expected to have a greater role as space tourism and other space activities are projected to grow. Nonetheless, it is important to note that many environmentalists acknowledge the indirect benefits that rocket launches have had to support the planet's health. For example, investment in rocket launches and launch infrastructures has led to advancements in transportation, battery energy storage, renewable energy production, and agriculture (Donou-Adonsou et al., 2024). Those benefits counter the negative impacts of rocket propulsion. Nonetheless, environmentalists are concerned

about the persisting negative consequences of rocket propulsion, especially as the industry continues to grow.

Another major social group involved in the conversation about rocket launches is academics. Stakeholders in academia, including students, researchers, and investors argue that rocket launches facilitate science missions that advance technologies and prosperity across various industries. Monte and Scatteia (2017) argue that investment in rocket development in Europe significantly contributed to technology developments, which led to the "creation of [physical or process] assets" that were also exploited in other markets. Furthermore, Donou-Adonsou et. al. argue that research and development facilitated by rockets have led to advancements in solar panels, energy storage, and agriculture, and those advancements help reduce rocketry's burden on the environment. Under the SCOT framework, academics view rocket launches as a means to transport instruments and science missions to the upper atmosphere.

Finally, the third relevant social group in this discussion is the local citizens and governments of municipalities that are affected by rocket launches. A launch pad or rocket development facility may attract high-paying jobs and investment. For example, Monte and Scatteia (2017) found that investment in rocket launch infrastructure increased GDP, employment, and growth in aerospace and non-aerospace industries. With that evidence, local governments may be inclined to invest in rocket launch infrastructure, regardless of their sustainability implications and how other social groups interpret rockets under the SCOT framework. Conversely, the citizens of a town that hosts an active launch pad may be critical of rocket activity because of the noise pollution. For example, citizens of Vandenberg in CA spoke up against frequent launches out of Vandenberg Space Force Base in a news article by a Coastal

View news outlet (Oki, 2024). Under this model and the SCOT framework, the municipalities view rockets as tools for bringing capital, jobs, and prestige to their area. Therefore, unlike academics, they might not necessarily prioritize the science and research missions facilitated by rocket launches.

**Conclusion**

There are several competing arguments for or against investing in rocket launch infrastructure. Advocates of rocket launches point to the economic benefits across aerospace and non-aerospace industries and advances in useful science and technology. However, skeptics of rockets highlight their significant and growing toll on the environment. Under the SCOT evaluative framework, one interpretation of rockets will eventually stabilize and become dominant, and power dynamics have a significant role in which social group's perspectives and interpretations prevail. Therefore, anyone involved in a conversation about rockets' merits or environmental drawbacks must be mindful of this topic's different and opposing perspectives. More specifically, legislators need to be conscious of the public's concerns about the environmental sustainability of a rapidly growing private launch sector. They must pursue and support legislation that encourages growth in rocket launch infrastructure but also mitigates the harmful environmental footprint of rocket launches.

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