WHAT ARE THE ENVIRONMENTAL IMPACTS OF ROCKET INDUSTRY AND HOW CAN THEY BE MITIGATED FOR SUSTAINABLE SPACE EXPLORATION?

Sanidhya Bajaj

ABSTRACT

This research paper delves into the profound environmental consequences associated with various stages of Rocketry. It investigates the environmental footprint arising from rocket manufacturing, fuel production, rocket transportation, and the act of launching itself. Additionally, a comparative analysis of greenhouse gas emissions between the rocket industry and the aviation industry is conducted, along with a projection of future comparisons. Furthermore, the study evaluates potential solutions to mitigate these adverse impacts and explores hypothetical alternative methods for launching rockets. The paper also examines the sustainability implications of rocket operations, presenting arguments both for and against their continued use.

(1.1) EMISSIONS FROM ROCKET LAUNCHES

- **Impact of initial emissions on the ground and nearby biodiversity**

At launch sites, rockets create low-lying exhaust, known as a ground cloud, which interacts with nearby ecosystems, leading to measurable environmental changes. During the space shuttle launch, solid rocket motors emitted hydrochloric acid which collected in nearby lagoons and acidified the water, leading to abrupt, moderate fish kills. The space shuttle's ground cloud also created significant amounts of acid rain and alumina deposition, damaging or killing nearby plants through direct contact or soil acidification. Similarly, scientists in China measured decreases in insect abundance and biodiversity in two nearby tropical plantations after a Long March 7 launch. It is true that at the current frequency of rocket launches, there is less impact on the flora and fauna. However, as the rate of rocket launch increases, there will be a considerable effect on the biodiversity of the nearby location, ultimately affecting the food chain (MIT Science Policy Review 2022).

- **Impact of emissions on the upper layers of atmosphere including Ozone**

As rockets ascend, the emissions react chemically with upper layers of the atmosphere. However, this tropospheric rocket exhaust is generally thought to have transient effects and is otherwise assumed insignificant in the greater troposphere layer. In the stratosphere, large rockets produce holes in the ozone layer above launch sites. Measurements of exhaust plumes of the Delta II rocket (burning Lox/Kerosene and ammonium perchlorate/aluminum) show 70 to 100% ozone loss in the region of the plume for at least 39 minutes Other studies show that the Ariane V rocket creates a launch site ozone hole for approximately four days. The exact environmental consequences of these local ozone holes are not well understood.
Solid rocket motors emit chlorine that can fuel ozone destruction. Chlorine is an efficient ozone depleter as it further goes through chemical reactions that deplete the ozone layer. Because the molecules created by chlorine repeat and perpetuate the cycle, chlorine emissions are typically considered one of the most serious SRM (Solid Rocket Motors) pollutants (MIT Science Policy Review 2022).

- **Impact of the falling booster on land/water**

Rocket launches often have multiple stages, and the boosters that fall off in the initial stages are often dropped over land and water, which can create toxic fuel leaks and impact craters. In Baikonur, Kazakhstan, the Russian Proton rocket stages left traces of a carcinogenic fuel, unsymmetrical dimethylhydrazine (UDMH), causing damage to the nearby surroundings. UDMH is a toxic substance and takes about 37 years to decompose (MIT Science Policy Review 2022).

(1.2) QUANTIFYING THE EMISSIONS FROM ROCKET LAUNCHES

FOR SLS ARTEMIS 1: (BBC 2022)

The Space Launch System (SLS) rocket is one of the most powerful rockets in the world, and its launch produces a significant amount of greenhouse gas emissions. According to a study by the University of Strathclyde, the Artemis 1 mission was expected to emit around 116 tonnes of carbon dioxide (CO_2) into the atmosphere. This is equivalent to the emissions of around 100 cars driven at normal use for a year (BBC 2022).
The main source of emissions from the SLS launch is the solid rocket boosters, which use a fuel called ammonium perchlorate. This fuel burns at a very high temperature, producing large amounts of CO_2. The liquid hydrogen and oxygen fuel used by the core stage of the rocket also produces some emissions, but these are much lower than the emissions from the solid rocket boosters (BBC 2022).
It is important to note that the greenhouse gas emissions from the SLS launch are relatively small compared to the emissions from other sources, such as transportation and energy production. However, as the number of rocket launches increases in the future, the environmental impact of spaceflight is likely to become more significant (BBC 2022).

Here are some other estimates of the greenhouse gas emissions from rocket launches:

- The Falcon 9 rocket, which is used by SpaceX, is estimated to emit around 27 tonnes of CO_2 per launch.
- The Soyuz rocket, which is used by Ros cosmos, is estimated to emit around 35 tonnes of CO_2 per launch.
- The Space Shuttle was estimated to emit around 16 tonnes of CO_2 per launch.
  (8 Billion Trees 2023)

It is important to note that these numbers are just estimates. The actual amount of emissions from a rocket launch can vary depending on a number of factors, such as the type of rocket, the amount of fuel used, and the weather conditions at the launch site.

(2) EMISSIONS FROM THE MANUFACTURE OF ROCKET FUEL

Manufacturing of fuels is another sector that contributes significantly to emissions, be it directly or indirectly. This section will cover emissions from the manufacture of widely used chemicals used as rocket fuels.

Liquid Hydrogen: It is one of the most common fuels used in modern rockets. It is a light and extremely powerful propellent, and is generally produced by the following methods-

a. Steam Methane reforming (Hydrogen Explained 2023)-
Commercial hydrogen producers and petroleum refineries use steam-methane reforming to separate hydrogen atoms from carbon atoms in methane (CH_4). In steam-methane reforming, high-temperature steam (1,300°F to 1,800°F) under 3–25 bar pressure (1 bar = 14.5 pounds per square inch) reacts with methane in the presence of a catalyst to produce hydrogen, carbon monoxide, and a relatively small amount of carbon dioxide (CO_2).
Natural Gas is the main methane source for hydrogen production by industrial facilities and petroleum refineries. Landfill gas/biogas, which may be called bio methane or renewable natural gas, is a source of hydrogen for several Fuel cell power plants in the United States. Biofuels and petroleum fuels are also potential hydrogen sources (Hydrogen Explained 2023).
This is the most prominent method of hydrogen production currently, but it is not eco-friendly as the raw materials are non-renewable and the products CO and CO_2 are harmful for the environment.

b. Electrolysis- (Hydrogen Explained 2023)
Electrolysis is a process that splits hydrogen from water using an electric current. Electrolysis itself does not produce any by-products or emissions other than hydrogen and oxygen. The electricity for electrolysis can come from renewable sources, nuclear energy, or fossil fuels. If the electricity for electrolysis is produced from fossil fuel (coal, natural gas, and petroleum) or biomass combustion, then the related environmental effects and CO_2 emissions are indirectly associated with that hydrogen.
This means of production is not available on a large scale at present because of high electricity requirements.
Research is underway to develop other ways to produce hydrogen and a few include:
Using solar energy technologies to split hydrogen from water molecules- Solar energy can assist in hydrogen production mainly through electrolysis, where electricity from solar panels is used to split water into hydrogen and oxygen. Two specialized methods include:

1. Photoelectrochemical Water Splitting: Directly uses sunlight-absorbing materials to initiate water splitting, eliminating the need for external electricity.

2. Solar Thermal Methods: Concentrated solar power heats reactors to high temperatures, facilitating chemical reactions that produce hydrogen.

Solar technology makes hydrogen production more sustainable, efficient, and potentially cost-effective.

2. **Liquid Oxygen** (Products):

Liquid Oxygen is produced by an air separation unit (ASU) through liquefaction of atmospheric air (The change of a gaseous substance into a liquid condition) and separation of the oxygen by continuous cryogenic distillation(A process of separation of gaseous mixture, using simple distillation, at high pressure and low temperature).
The oxygen is then removed and stored as a cryogenic liquid which is highly flammable.
If the electricity used for manufacturing Liquid Oxygen is produced from fossil fuels, then this factor will add up in the environmental impact of producing oxygen. Using electrolysis can be a helpful way to produce oxygen and hydrogen (both are used as rocket fuel) as it only requires water and electricity.

3. **Kerosene** (Medicine 2013):

Kerosene is widely used as a rocket fuel. It can be produced from distillation of crude oil (straight-run kerosene) or from the cracking of heavier petroleum streams (cracked kerosene). Raw kerosene has properties that make it suitable for mixing with performance additives for use in a variety of commercial applications, including transportation fuel.
It releases Carbon Dioxide, a greenhouse gas which absorbs and traps the heat radiated from the Sun. This increases the global temperatures and thus contributes to climate change.

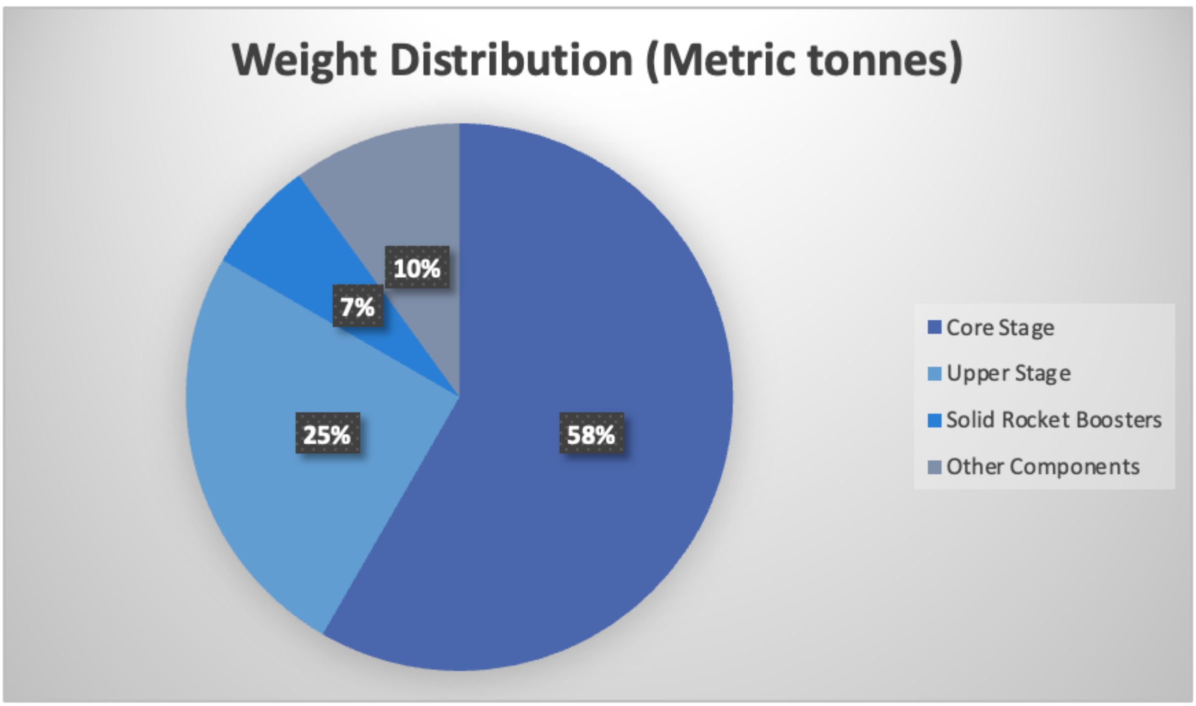
4. **Methane** (High environmental impact rocket propellants 2022)

Although Methane is not widely used when compared to RP-1, it is more powerful and a bit cleaner as compared to RP-1. SpaceX (Raptor engine), ISRO, and Blue Origin (BE4 engine) are working on Methane-powered engines which may replace RP-1 completely in the future.
Methane, when completely burnt, releases Hydrogen Dioxide and Carbon Dioxide.

(3) EMISSIONS FROM THE MANUFACTURE OF ROCKET BODY

Apart from the making of fuels for the rocket, another significant environmental factor is manufacturing the rocket body and parts. The following figures come from the SLS (Space Launch System) body and other materials involved.
The SLS is made of approximately 10,000 tons of materials. The core stage of the SLS is made of 7,000 tons of materials, while the upper stage is made of 3,000 tons of materials. The solid rocket boosters are made of 800 tons of materials each. The total weight of the SLS before launch is 5.75 million pounds, or 2.59 million kilograms (Mohon 2023)

Here is a breakdown of the materials used to make the SLS: (Mohon 2023)



Core stage: 7,000 metric tons of aluminum, steel, and carbon fiber composites

Upper stage: 3,000 metric tons of aluminum, steel, and carbon fiber composites

Solid rocket boosters: 800 metric tons of aluminum and steel

Other components: 1,200 metric tons of various materials, including avionics, and insulation.

Estimates of CO_2 emissions from the basic materials required to build a rocket:

1 kg of aluminum 2024	16.5kg of Co2 gas (Berker 2022)
1 kg of steel	2.2 kg of Co2 gas (Sustainable Ships)
1 kg of carbon fiber	24 kg of Co2 gas (Sakamoto 2021)

NASA has not given any official statement on the ratio of materials used. Additionally, aluminum is primarily used for the rocket body because of its lightness and durability. Moreover, there are a lot of minor components used in the rocket body which are hard to account for carbon emissions. Hence, I have assumed that 90% of the rocket body is made from aluminum alloy 2024 and 10% from carbon fiber and steel components for ease of calculation (Bardan 2023)

CALCULATION OF THE FUEL EMISSIONS-

Rocket Body from aluminum alloy 2024 (90% of the total body) :
90% of total mass of the rocket body* carbon emissions from 1 kg of aluminum =
0.90(12000*1000*16.5)= 1.782*10^8 kg

Rocket body from carbon fiber and steel components (10% of the total body)
10% of the body* average of carbon emissions from 1 kg of carbon fiber and steel =
0.10(12000*1000*13.1)= 1.572*10^7 kg– (Here 13.1 is the average emissions per kg from steel and carbon fiber)

Adding these two values, we get 1.9392*10^8 kg of carbon emissions, equivalent to the emissions from about 45,000 cars on normal use in the U.S. annually.

(4) EMISSIONS FROM ROCKET TRANSPORTATION AND STORAGE

The rocket industry includes multiple stages from making to the launching of the rocket, and fuel transportation and storage is one of them. The transportation and storage of rocket fuel emit greenhouse gasses and pollutants due to fuel production, energy-intensive transportation, and specialized storage facilities. Volatile organic compounds can be released during handling, while leaks, spills, and venting before launch can lead to emissions. Even during storage, chemical reactions and fuel decomposition contribute to the release of gasses and by-products. Efforts to minimize these emissions are ongoing, including the development of more sustainable fuel options and improved handling practices. (Indoor Air Quality 2023)

For evaluating the emissions from transporting the rocket to the launching site, I have considered the NASA Crawler as a base example. The NASA Crawler is a colossal vehicle used to transport space shuttles and rockets from the Vehicle Assembly Building to the launch pad at Kennedy Space Centre.
The carbon footprint of the NASA Crawler depends on the fuel consumed for the transportation. It has two 2500 gallons of tanks filled up before any trip. It uses 1 gallon for 32 feet of movement, meaning 165 gallons per mile (NASA, Crawler Nasa 2023)

The nearest launchpad, 39B, is 4.2 miles away, which means that the crawler has to travel for 8.4 miles at minimum (NASA, Crawler Nasa 2023). Hence about 1400 gallons of diesel is used for the shortest trip!
Of course, the actual amount of emissions will increase as the distance increases.

In order to reduce the environmental impact of the Crawler, NASA is considering using a more efficient electric vehicle in the future. However, this would require a significant investment in infrastructure, as the Crawler needs to be able to carry very heavy loads (NASA, Crawler Nasa 2023)
Here are some other ways to reduce the carbon footprint of the Crawler:

- Use more efficient engines which can produce more energy using less amount of fuels.
- Use lighter fuels- using fuels that are lighter in weight can reduce the total load that the crawler has to carry, thereby reducing its fuel consumption.

By taking these steps, NASA could significantly reduce the environmental impact of the Crawler and make space exploration more sustainable. (NASA, Crawler Nasa 2023)

CALCULATIONS:

The following is the calculation for the emissions produced from the crawler. This will give an idea for the emissions produced in transporting rockets. However, we should keep in mind that a lot of other rocket launching companies don't produce this much Co2 as they use other means of transportation.

Amount of fuel required per mile-165 gallons per mile
-10.43 Kg of CO_2 emissions is produced from 1 gallon of diesel fuel
-Distance from Kennedy's Vehicle Assembly Building to launch complex 39B- 4.2 miles one way. (NASA, Crawler Nasa 2023)

Hence, 10.43*165= about 1720.95 kg of CO_2 emissions per mile.

Therefore, to reach 39B (launch site), the crawler will emit (1721*8.4) about 14,456 kg of CO_2, equivalent to the emissions from 3.2 cars on normal use in the U.S. annually.

(5) COMPARISON BETWEEN ROCKET AND AVIATION INDUSTRY

It is evident that rockets produce a lot of CO_2 emissions. For the sake of comparison, I will compare the rocket industry with the aviation industry in terms of the carbon emissions they produce (8 Billion Trees 2023)

COMPARISON BETWEEN A SINGLE ROCKET AND AIRPLANE:

Falcon 9-
The rocket industry has a wide range of models with diverse uses. Therefore, I will cover a single rocket model with one use case to avoid making the analysis convoluted. I have specifically chosen the Falcon 9 because of its high frequency of launches and long-term viability for transportation of payload in space.

Emissions from Falcon-9 (Zaremba 2017):

The Falcon 9B uses 29,600 gallons of fuel, equivalent to 112,184 Kg, of kerosene per launch (8 Billion Trees 2023)
For each kilogram of kerosene burned, 3 Kg of CO_2 goes into the air (8 Billion Trees 2023)
Also, manufacturing Kerosene further produces carbon emissions.
As 1 kg of kerosene produces 2.7 kg of CO_2,
112,184 Kg x (3 + 2.7) = 639448 Kg~ 640 metric tonnes of CO_2 emissions.

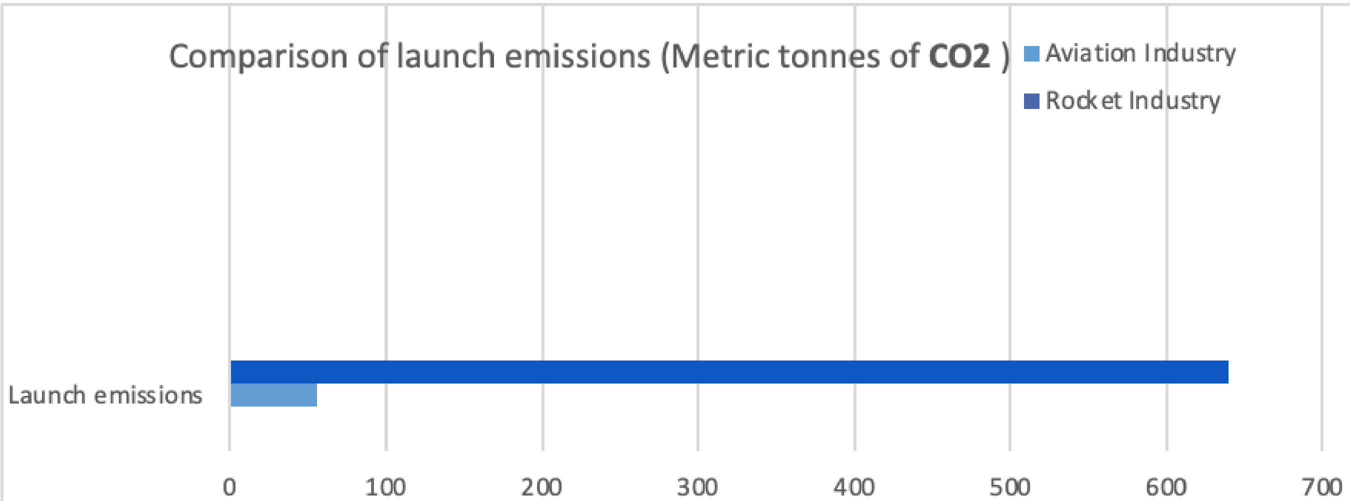
That means 640,000 kilograms of CO_2 goes into the atmosphere every time Falcon 9 is launched. While that is just an approximation, it paints a picture of what multiple launches would do to the environment. For comparison, the emissions from 143 cars on normal use in the U.S. is equivalent to this figure.

Boeing 737- The Boeing 737 was used as a model for commercial flights as it is one of the most commonly used airplanes for passenger flights.

Emissions from Boeing 737: (Science Focus)
According to BBC Science Focus, a Boeing 747 uses 7840 kgs of fuel pe5r 250 kms, with 10.1 kg for additional 1 km. Considering that the average flight distance globally is about 981 km, the calculation gives: (Science Focus)

250 + 731 kms= 7840 + 7383.1= 15223~ 15250 kgs of fuel used.
Jet A-1 fuel CO_2 emission rate: 1 kg of fuel produces 3.16 kgs of CO_2

Jet fuels produce about 0.5 kg of carbon emissions from 1 kg of fuel manufactured: (ICAO)
Hence, 15223 x (3.16+0.5) = 55,716 kg~ 55.7 metric tonnes of CO_2



The aforementioned contrasts indicate that rockets generate roughly 11.5 times more carbon emissions during launch compared to airplanes. It's important to note that these numbers can differ based on various factors like model types, duration, objectives, and fuel varieties. However, precise quantitative data on these aspects is absent from the industries' reports, which is why they are not subjected to a comparative analysis in the context of this study.

However, when we compare the two industries' emissions, the conditions change drastically: The rocket industry emits about 1000 metric tonnes of black carbon (a sooty black material that is a component of fine particulate matter) into the atmosphere each year, according to Piercing's 2022 report. In contrast, the aviation industry releases 834 million metric tonnes of overall carbon emissions annually.

This is about 834,000 times more than the rocket industry. This is stated in a 2022 revised issue brief on greenhouse gas emissions from commercial aviation. It's important to note that while black carbon stays in the atmosphere for only a few days, compared to thousands of years for CO_2, it is about 1500 times more harmful during its short presence. This comparison, although not entirely apples-to-apples, provides a sense of the relative scale of environmental impact between the two industries.

This massive deviation occurs mainly because of the frequency of rocket and airplane launches; about 180 (Nature 2023) rockets are launched annually (in 2022) compared to 22.2 million (Finance Online 2021) annual airplane launches (in 2021).

(6) HOW REUSABLE ROCKETS CAN IMPACT THE ENVIRONMENT

Rockets pollute, but a sustainable approach may or may not cause less pollution. Sustainability means reusability, but reusability in the long term is expected to reduce prices, which is expected to increase the number of launches.

Similar to NASA, SpaceX and Blue Origin are focusing on fully-reusable systems. However, only partially-reusable systems have so far been practical. Unsurprisingly, partially-reusable systems have single-use sections, typically the orbital inserter. These sections help to place the rocket in orbit of Earth, and these cannot be reused. Most systems recover launch systems and shuttles, either through atmospheric re-entry or planned landing. As it stands, these are the most practical uses of reusable launchers, although SpaceX plans to test a fully-reusable launcher in 2023 (Reusable Rockets and the Environment 2020).

A case study was conducted comparing a non-reusable Falcon 9 and a reusable Falcon Heavy. The two rockets were analyzed using a sustainability assessment that evaluated the environmental, economic, and societal impact of the two rockets. The environmental portion of the study was conducted on a per unit mass basis where the non-reusable Falcon 9 was the baseline. The study demonstrated that the reusable Falcon Heavy reduced costs by 65% and global warming potential by 64%. Global warming potential is an important metric by which different pollution emitters are standardized and used to be compared to one another. A large contribution to Global warming is from the manufacture of a rocket, which is eliminated from reusing the rocket again and again, thus reducing the impacts contributing to global warming (A. Torres 2020)

One of the main factors driving down the cost of space launches is the industry's focus on sustainability and competitiveness. Often, making a product more sustainable also leads to improvements in cost and overall performance.

Reusable Rockets- benefits, drawbacks, and long-term viability-

The most obvious benefit of a reusable rocket is cost savings. Unsurprisingly, it’s much cheaper to refurbish and relaunch a rocket than it is to build a new one – it can be up to 65% cheaper (Reusable Rockets and the Environment 2020). Reusable rockets also use less fuel than their expendable counterparts, making them comparatively better for the environment. However, they have disadvantages too. The main drawback of reusable rockets is their reduced payload. By extension, they must be built to survive the difficulties of launch and re-entry, meaning there are more stabilization fins and additional equipment. In turn, this means the rockets are relatively heavier. Additionally, Reusable rockets must be refurbished and tested before each new launch. These processes obviously take time and resources to ensure the launchers are at an appropriate standard. However, this amounts to far less time and fewer resources than building and launching expendable rockets. For a long-term perspective, Reusable rockets are great for carrying lighter payloads like satellites and small probes. They not only reduce the green-house emissions from manufacturing a rocket again and again but also reduce time and cost drastically.

(7) 3-D PRINTING TECH AND SUSTAINABLE FUEL PRODUCTION

Another option is to switch the manufacture of engines to 3D printing, which is what launch company Orbex is attempting. It has designed a custom-made industrial 3D printer to produce rocket engines. This will help to reduce waste and production time, but will also help reduce overall weight, making the rocket more fuel-efficient (Orbex 2021)

The rocket produced by Orbex uses BioLPG, an ultra-low carbon fuel produced by Calor. BioLPG is biologically created LPG (propane) that is slightly worse than methane when in terms of fuel performance. The two companies announced their partnership in late 2021 and have already tested the fuel against traditional kerosene rocket fuel (Orbex 2021)

Orbex plans to offset carbon emissions from rocket production and transport, and its launch site, Sutherland Space Port, will be entirely carbon neutral during production and operation. (Orbex 2021)
There's no denying that Orbex is setting a pretty high bar for sustainability in the space industry. A 96% reduction in carbon emissions is a massive benchmark and, provided it's viable, it'll be interesting to see what impact this has on the space industry as a whole.

An important distinction, too, is where the carbon reduction comes from. Orbex's BioLPG creates less carbon during the production process rather than the launch itself, although, as the study results show, this does have an impact. Fuel production is arguably a bigger concern for now, as there currently aren't really enough rocket launches for launch emissions to be a massive concern.
Numerous other companies have followed suit, including Skyrora, which is developing a system for making kerosene from plastic. Like Orbex, its plan is to reduce carbon emissions during the production process more than the launch itself. (KDC Resource)

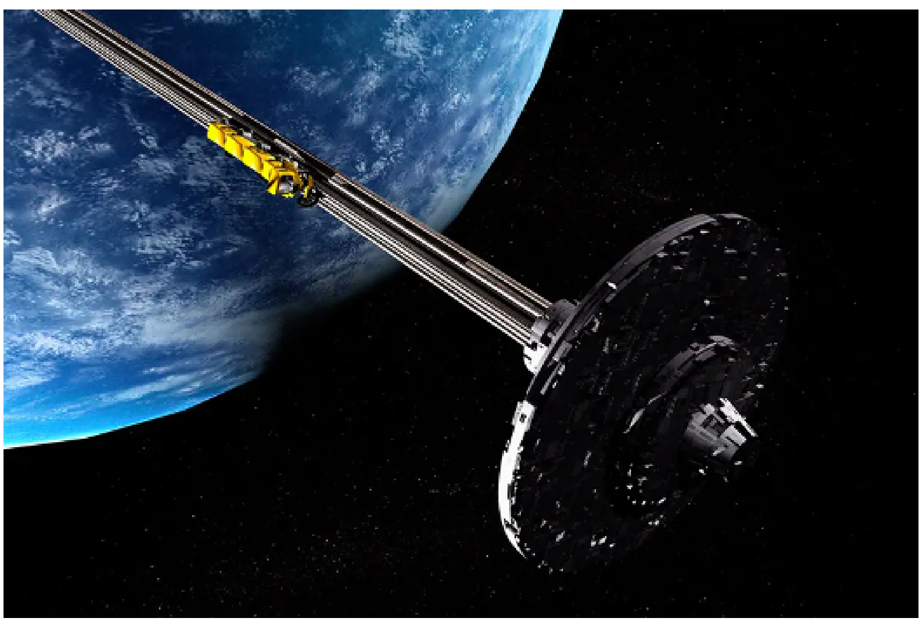
Although the space industry is currently in no rush to change the fuel production methods, it would be necessary to shift to sustainable production in the future when space is commercialized and the launch frequency has increased by a considerable margin.

(8) NON-ROCKET SPACE LAUNCHES

Today, there is a universal reliance on rockets to send payloads and humans in space. However, there are theoretical concepts for launch into space where much of the speed and altitude needed to achieve orbit is provided by a technique that is not subject to the limits of the rocket equation. These concepts come under the umbrella term of Non-Rocket Space Launches. Here I have covered four interesting NRLs which are relatively reasonable and can be possibly achieved in the future.

Space Elevator- 7.1

A space elevator is a proposed transportation system that could take people and cargo from the surface of a planet directly into space without the use of large rockets. The system would consist of a cable anchored to the surface, extending into space, and attached to a counterweight in space beyond geostationary orbit. The cable would be held up, under tension, and stationary over a single position on Earth by the competing forces of gravity and the upward centrifugal force. With the cable deployed, climbers (crawlers) could repeatedly climb up and down the cable by mechanical means, releasing their cargo to and from orbit. (ISEC 2016) However, available materials are not strong and light enough to make an Earth space elevator practical. Potential future advances in carbon nanotubes (CNTs) could lead to a practical design, although some sources believe that CNTs will never be strong enough. Other possible future alternatives include boron nitride nanotubes, diamond nano threads, and macro-scale single crystal graphene.

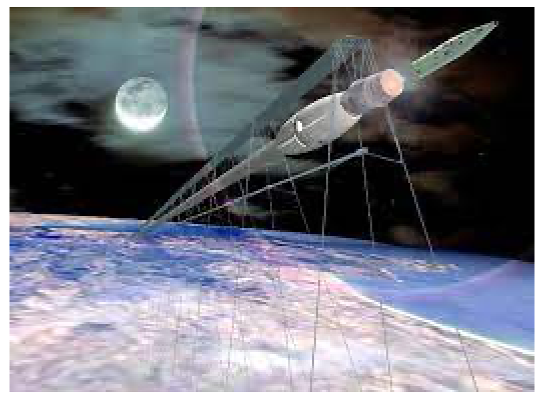


The concept is also applicable to other planets and celestial bodies. For locations in the solar system with weaker gravity than Earth's, such as the Moon or Mars, currently available materials such as Kevlar could be practical as the cable material for elevators there. (ISEC 2016)

Sky Tram-7.2

StarTram is a proposed space launch system propelled by maglev technology. Instead of using a rocket for gaining escape velocity, the spacecraft can be sent at extremely high speeds using a trail with maglev, spanning over about a few hundred kms to gain acceleration. (contributors 2023)

The Gen-1 system proposes to accelerate uncrewed craft at 30 g through a 130-kilometer (81 mi) long tunnel, with a plasma window preventing vacuum loss when the exit's mechanical shutter is briefly open. In the reference design, the exit is on the surface of a mountain peak of 6,000 meters (20,000 ft) altitude, where 8.78 kilometers per second (5.46 mi/s) launch velocity at a 10 degree angle takes cargo capsules to LEO when combined with a small rocket burn providing 0.63 kilometers per second (0.39 mi/s) for orbit circularization.



With a bonus from Earth's rotation if firing east, the extra speed, well beyond nominal orbital velocity, compensates for losses during ascent including 0.8 kilometers per second (0.50 mi/s) from atmospheric drag. (contributors 2023)
We can use nuclear reactions (which is environmentally friendly) to power the Sky Tram as it would require a lot of electricity to power the whole system.

Sky Tram will not only make the emission factor negligible, it will also significantly reduce the cost/kg of payload: going from $10,000-$25,000 per kilogram to just $43 per kilogram. (STAR TRAM)
However, the initial cost of making the structure would be very high: estimated about 19 billion dollars for Gen-1. Moreover, it is crucial to power the Sky Tram with a sustainable and clean source of energy because of its high energy requirements. (STAR TRAM)

Spin Launch-7.3

Spin Launch is a start-up company which aims to send small payloads in space using the kinetic energy gained by spinning the spacecraft at very high speeds. After reaching a critical speed, the craft will launch at 2.08 km/s.
The rocket then ignites its engines at an altitude of roughly 200,000 ft (60 km) to

reach orbital speed of 7.666 km/s with a payload of up to 200kg. Other than the initial infrastructure cost, this system requires low maintenance and is thus more efficient than traditional rockets in terms of expenditure. (SPIN LAUNCH)
Spin launch method produces negligible emissions when compared to chemical rockets; this is promising for frequent launches of small payloads without much maintenance and environmental impacts. Another factor to consider is using a clean energy source to power the whole system, which will further make it more sustainable. (SPIN LAUNCH)
However, there are some problems with this NRL:
Liquid propellants cannot be used because they cannot remain stable under the magnanimous centripetal force produced while spinning.
The current design tested is only viable for small payloads.

Hybrid Launch System-7.4
This system involves launching rockets from a high-altitude aircraft, such as a modified Boeing 747. The rocket is carried to a predetermined altitude before being released and ignited. This method has the potential to reduce the amount of fuel needed for launch.
In 2010, NASA suggested that a future ramjet aircraft might be accelerated to 300 m/s (a solution to the problem of ramjet engines not being startable at zero airflow velocity) by electromagnetic or other sled launch assist, in turn air-launching a second-stage rocket delivering a satellite to orbit. (contributors 2023)

This method would require the second-stage propulsion to gain the critical velocity. This method would be complex as it requires multiple systems. However, it completely eliminates the need of first-stage rocket propulsion, thus allowing reduction in its individual complexity or cost. (contributors 2023)
Most of the emissions from a chemical rocket are produced during the first-stage. Hence, Hybrid Launch System would relatively produce less emissions at the cost of delivering only small payloads. (contributors 2023)

(9) NUCLEAR ROCKET PROPULSION

Nuclear rocket propulsion is a type of thermal rocket where the heat from a nuclear fission replaces the chemical energy of the propellants in a chemical rocket. The basic idea behind nuclear rocket propulsion is to take advantage of the high energy density of nuclear reactions to achieve higher specific impulse compared to traditional chemical rocket engines. In a nuclear thermal rocket, a liquid propellant (generally liquid hydrogen) is pumped through a nuclear reactor core. The heat from the reactor core heats up the propellant, causing it to vaporize and expand. The expanded propellant is then expelled through a nozzle, creating thrust. (Bardan 2023)

Nuclear rocket propulsion is much cleaner than chemical propulsion as it does not produce any harmful emissions. However, the radioactive element used should be carefully disposed of as it can contaminate the environment for centuries.

Nuclear rocket propulsion has other benefits and challenges too:

- Here are some of the benefits of nuclear rocket propulsion: (Bardan 2023)

Increased payload capacity: Nuclear rockets can carry much more payload than chemical rockets, which means that they can be used to send larger spacecraft to distant destinations.
Increased range: Nuclear rockets can travel much farther than chemical rockets, which means that they can be used to explore the outer solar system and beyond.

- Here are some of the challenges of nuclear rocket propulsion: (Bardan 2023)

Safety: Nuclear rockets must be very carefully designed and operated in order to prevent accidents.
Radiation shielding: The nuclear rocket must be shielded from radiation in order to protect the crew and equipment.

The Department Of Energy is working with NASA to help test, develop and assess the feasibility of using new fuels that require less uranium enrichment for NTP systems. This fuel may be made using new advanced manufacturing techniques and can potentially help reduce security-related costs that come with using highly enriched fuel (NASA 2023)

Idaho National Laboratory is currently helping NASA develop and test fuel composites at its Transient Reactor Test (TREAT) facility to examine how they perform under the harsh temperatures needed for nuclear thermal propulsion. Initial testing has shown that nuclear fuels under development by NASA and DOE are capable of withstanding ramps up to operational nuclear thermal propulsion temperatures without experiencing significant damage. (Laboratory 2020)
Overall, NRP is a viable technique for more efficient rockets and it is a promising solution for sustainable space explorations in the coming future.

CONCLUSION

The research paper explored the direct and the indirect ways in which the rocket industry produces emissions. An extensive comparison between this and the aviation industry was conducted, while also projecting a plausible future scenario. Furthermore, different ways in which this industry can be improved in terms of emissions were evaluated. In conclusion, the rocket industry has various sectors that produce emissions at different scales. This industry holds a negligible stake in today's global emissions, and hence it is not taken as seriously as other industries are taken into account. However, it is essential to recognize the tremendous potential this field holds, particularly with the prospect of commercializing space for tourism, launching more satellites to improve communication, and enabling more efficient space missions and explorations. Companies like SpaceX and Blue Origin have optimistic plans for the future for these ventures. If everything goes as predicted, the rocket industry may eventually emerge as a prominent contributor to greenhouse emissions in the near future, which would likely arise as a major concern. To safeguard our planet's well-being, it is crucial to continually strive for improvements in all sectors, even if they seem to have a minimal impact, as collectively, these efforts can help mitigate the overall carbon footprint and create a more sustainable future.

This paper gives a basic idea on the environmental impacts of the rocket industry with some ways to mitigate it. Subsequent research endeavors will delve deeper into strategies for reducing this concern, emphasizing practical approaches such as exploring various fuel compositions and alternative launch mechanisms.

Bibliography

NASA. n.d. NASA. https://www.nasa.gov/exploration/systems/sls/index.html.
n.d. Atmospheric impact of space launches. Research Paper, MIT .
Torres, Andres. 2020. Reusable Rockets and the Environment. University of California, Merced.
Travel, Transforming Economics of Space. n.d. Transforming Economics of Space Travel.https://www.kdcresource.com/insights/the-rise-of-reusable-rockets-transforming-the-economics-of-space-travel/#:~:text=Reusable%20rockets%20also%20use%20less,a%20greater%20range%20of%20companies.
2023. 8 Billion Trees. 30 March.
https://8billiontrees.com/carbon-offsets-credits/carbon-footprint-of-space-travel/#:~:text=The%20Falcon%209%20B%20uses,Kg%20of%20kerosene%20per%20launch.&text=For%20each%20kilogram%20of%20kerosene,2%20goes%20into%20the%20air.&text=That%20means%20336%2C552.
2023. NASA.
https://www.energy.gov/ne/articles/6-things-you-should-know-about-nuclear-thermal-propulsion.
2022. “MIT Science Policy Review.” MIT. 29 August.
https://sciencepolicyreview.org/wp-content/uploads/securepdfs/2022/08/MITSPR-v3-191618003013.pdf.
Zaremba, Haley. 2017. “HuffPost.” HuffPost. 8 August.
https://www.huffpost.com/entry/how-much-fuel-does-it-take-to-get-to-the-moon_b_598a35b5e4b030f0e267c83d.
n.d. “ICAO.” ICAO. https://www.icao.int/environmental-protection/pages/climate-change.aspx.
n.d. KDC Resource . https://www.kdcresource.com/.
n.d. Wikipedia. https://en.wikipedia.org/wiki/Non-rocket_spacelaunch.
2016. ISEC. 2 May.
https://web.archive.org/web/20170326131735/http://www.isec.org/index.php/what-is-a-space-elevator.
n.d. STAR TRAM. https://startram.com/resources.
n.d. “SPIN LAUNCH.” SPIN LAUNCH. https://www.spinlaunch.com.
BBC. 2022. BBC. 15 July.
https://www.bbc.com/future/article/20220713-how-to-make-rocket-launches-less-polluting.
2023. “Hydrogen Explained.” U.S. Energy Information Administration . 23 June.
https://www.eia.gov/energyexplained/hydrogen/production-of-hydrogen.php#:~:text=The%20two%20most%20common%20methods,hydrogen%20production%20methods%20or%20pathways.
Products, Air. n.d. Liquid Oxygen.
https://www.airproducts.com/gases/liquid-oxygen#:~:text=Oxygen%20is%20produced%20by%20an,stored%20as%20a%20cryogenic%20liquid.
Medicine, National Library Of. 2013. Kerosene . 25 May.
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3664014/#:~:text=Kerosene%20can%20be%20produced%20from,commercial%20applications%2C%20including%20transportation%20fuel.

2022. High environmental impact rocket propellants. 13 September. https://universe.wiki/2022/09/13/high-environmental-impact-rocket-propellants/#:~:text=Methane%20is%20a%20powerful%20greenhouse,due%20to%20its%20combustion%20efficiency.
Mohon, Lee. 2023. “Space Launch System.” NASA. 22 August. https://www.nasa.gov/exploration/systems/sls/index.html.
NASA. 2023. “Crawler Nasa.” April. https://www.nasa.gov/sites/default/files/atoms/files/combined_crawler-transporters_fact_sheet_final.pdf.
Pearce, Carla. n.d. Science Focus. https://www.sciencefocus.com/future-technology/how-many-cars-equal-the-co2-emissions-of-one-plane.
Torres. 2020. “Reusable Rockets and the Environment.” eScholarship.https://escholarship.org/uc/item/1v52510j.
Thomas, Daniel. 2023. Investopedia. April. https://www.investopedia.com/terms/s/sustainability.asp.
contributors, Wikipedia. 2023. “Non-Rocket Space launches.” Wikipedia. 31 July. https://www.investopedia.com/terms/s/sustainability.asp.
Bardan, Roxana. 2023. NASA. 25 January. https://www.nasa.gov/press-release/nasa-darpa-will-test-nuclear-engine-for-future-mars-missions.
Laboratory, Idaho National. 2020. https://inl.gov/nuclear-energy/space-the-next-frontier-requires-innovation-in-nuclear-fuel-design-and-testing/.
Berker, Archy De. 2022. carbonchain. https://www.carbonchain.com/blog/understand-your-aluminum-emissions#:~:text=Around%2016%20tonnes%20of%20CO,burning%205%20tonnes%20of%20oil.
n.d. Sustainable Ships. https://www.sustainable-ships.org/stories/2022/carbon-footprint-steel#:~:text=Steel%20carbon%20footprint&text=The%20IEA%20estimates%20that%20direct,of%20CO2%20per%20ton%20steel.
Sakamoto, Kaito. 2021. Science direct.https://www.sciencedirect.com/science/article/abs/pii/S2214993721001202#:~:text=The%20total%20GHG%20emission%20resulting,representing%2020%25%20GHG%20emission%20reduction.
2023. “Indoor Air Quality .” EPA. https://www.epa.gov/indoor-air-quality-iaq/what-are-volatile-organic-compounds-vocs.
Piesing, Mark. 2022. “The pollution caused by rocket launches.” BBC Future.https://www.bbc.com/future/article/20220713-how-to-make-rocket-launches-less-polluting#:~:text=Maloney%20and%20his%20team%20calculated,black%20carbon%20into%20the%20stratosphere.

2022. "Issue Brief | The Growth in Greenhouse Gas Emissions from Commercial Aviation (2019, revised 2022)." EESI.
https://www.eesi.org/papers/view/fact-sheet-the-growth-in-greenhouse-gas-emissions-from-commercial-aviation#:~:text=Airline%20Energy%20Intensity%20and%20Emissions,-Between%201970%20and&text=According%20to%20the%20International%20Council,30%20percent%20in%.
2021. Finance Online.
https://financesonline.com/number-of-flights-worldwide/#:~:text=The%20number%20of%20domestic%20and,2021%20(OAG%2C%202021).
2023. Nature. January .
https://www.nature.com/articles/d41586-023-00048-7#:~:text=2022%20was%20a%20record%20year%20for%20space%20with%20180%20successful,the%20Chinese%20government%20and%20businesses.
2021. "Orbex." Orbex. 26 February .
https://orbex.space/news/orbex-commissions-largest-industrial-3d-printer-in-europe-for-rapid-rocket-building.