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Space sustainability isn't just about space debris: On the atmospheric impact of space launches

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HIGHLIGHTS

- Space launch activities generate direct emissions of combustion products into different layers of the atmosphere, inducing ozone depletion and affecting Earth's energy balance
- Scientific understanding of the implications and magnitude of this impact is insufficient, and the expected growth of the sector makes it a pressing issue
- International regulation is virtually absent on this topic and local policies are scarce
- The development of actionable and common life cycle sustainability metrics dedicated to launch vehicles could be beneficial to the sector

Throughout their life cycle, space launch vehicles impact their local and global environments on Earth and in space. Given the space industry's projected growth, recent literature suggests that the atmospheric consequences of these activities are understudied and insufficiently addressed. Rockets uniquely emit combustion gases and particles into distinct layers of the atmosphere, inducing effects that include perturbations of ozone chemistry and of Earth's energy balance through radiative forcing. International environmental regulations do not presently address rocket emissions and only scarce, isolated policies exist at the national level. Additional research on the impact of space launches, including new *in situ* measurements coupled with global atmospheric models, is required to inform policymaking and future mitigation. The development of an actionable and collaborative sustainability index for launch vehicles could serve as a basis for future regulations or incentivize the sector towards more sustainable designs by making emissions reduction a competitive advantage.

The year 2021 was a turning point for the private spaceflight industry. Among the commercial firsts in the space sector, two companies—Blue Origin and Virgin Galactic—began to offer space tourists tickets for suborbital spaceflights. In addition, SpaceX achieved a record number of launches, including the first all-civilian spaceflight, and NASA awarded contracts for new private space station concepts. To provide global internet services, projects of mega-constellations—very large networks of satellites—are also being developed. The proposed size of these constellations continues to grow, with SpaceX filing for up to 42,000 Starlink satellites and Amazon booking 83 launches to deploy most of its Kuiper constellation over the next five years [1]. For reference, in 2015, only 1300 active satellites were orbiting the Earth, and 82 rockets were successfully launched worldwide (Fig. 1). However, as the commercial space industry flourishes, offering new services to people and businesses on Earth, it also generates its share of negative environmental externalities.

Space technologies are valuable assets for environmental protection and can support the United Nation's (UN) Sustainable Development Goals on Earth, but these technologies also have environmental impacts. Recent policy has been focused on space debris, the in-space pollution that satellites and rocket bodies produce in orbit. While orbital debris may well be viewed as the most consequential threat from current space activities, the appropriate scope to understand the full environmental cost of the expanding space industry also encompasses ground and atmospheric consequences [2]. As such, researchers have called for further study on rocket emissions—the combustion gases and particles emitted into different layers of the atmosphere during launches, landings, and reentries of rockets—that can interact with ozone chemistry and affect global climate in poorly understood ways [3, 4]. While the scientific understanding is limited, studies suggest that the impact of rocket emissions will continue to grow with increased launches and may reach unsustainable levels [3]–[6].

Regulatory responses to any perceived environmental impacts of space launch activities have been almost nonexistent for decades. However, as the industry gains visibility, propositions to develop such policies are starting to appear. Taxes on space tourism have, for instance, been discussed in the United States (U.S.) at the federal level (1).

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This article explores the current scientific understanding of launch vehicles' atmospheric impact before offering an overview of existing policies and alternatives to ensure a more sustainable future for the space sector.

Rocket science and atmospheric emissions

Orbital launch vehicles vary significantly in their design and capabilities. One of the smallest operational rockets is Rocket Lab's Electron, which measures 18 m tall for about 11.3 t of propellant and delivers up to 300 kg of small satellites to low Earth orbit (LEO) [7]. On the other hand, the Space Launch System (SLS), NASA's super heavy-lift launch vehicle, stands at 111 m with a propellant mass over 2500 t. SLS can inject up to 45 t of payload, including the crewed capsule Orion, to lunar vicinity in its most powerful configuration, and is expected to become operational in 2022 [8].

The key factors driving a rocket's atmospheric impact are the type and mass of propellant, the engine design, and its trajectory through the atmosphere.

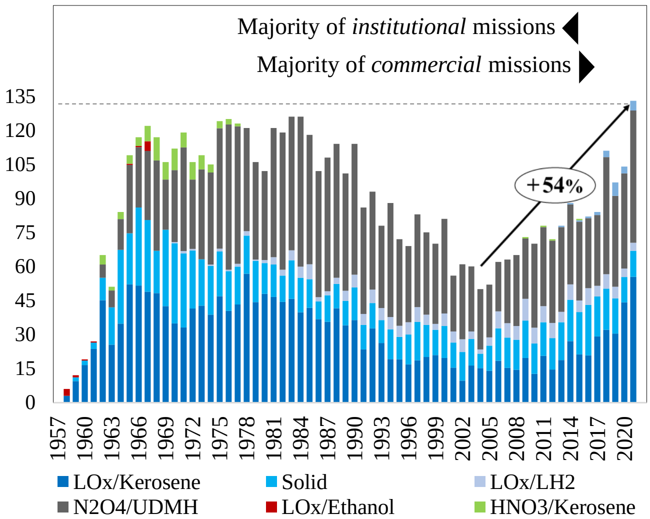

Figure 1: Total number of successful orbital launches per year worldwide (1957–2021), broken down by main type of propellants used (both first stage and booster(s) are accounted for, cumulatively). Commercial missions primarily drove the 54% growth since 2001. Data: [9, 10]

Firing through the atmosphere

Most orbital launchers are used to deliver satellites to LEO, usually below 900 km, or to geosynchronous orbit (GEO) at an altitude of about 36,000 km. In an attempt to define where space begins, the Kármán line—situated at an altitude of 100 km—was proposed and is used today by various international organizations as a frontier between Earth's atmosphere and outer space. Below the Kármán line, the atmosphere is divided into the troposphere (up to 10–15 km), stratosphere (10–15 to 45–55 km), and mesosphere (45–55 to 80–90 km) [11]. Launch vehicles emit through each layer of the atmosphere up to the Kármán line and above (see Fig. 2). In comparison, civil aviation operates near the boundary between the troposphere and the stratosphere. By emitting combustion products directly into the stratosphere and higher, a rocket's launch and reentry have impacts that are distinctive from any other industry. Since gas exchanges between atmospheric layers are very slow, the location of rockets' direct emissions will relate to the altitudes with potential for interactions with atmospheric chemistry and risk for particle accumulation [11]. Stratospheric emissions are a particular source of concern because 90% of the atmospheric ozone is found in the stratosphere, with the highest concentrations in the ozone layer (from 15–35 km) [12]. Stratospheric ozone acts as a natural protection for Earth by absorbing most of the ultraviolet radiation coming from the Sun, which is harmful to life [13].

The diversity of rocket propellants and engines

The choice of rocket propellant and engine used are major design considerations and determine a rocket's exhaust composition. Table I summarizes the most common propellants and examples of launchers using them. The two most common types of rocket propellants are liquid bipropellants and solids. Liquid bipropellants consist of a liquid fuel and a liquid oxidizer that react together in the combustion chamber. In solid rocket motors (SRMs), a solid mixture stored within the combustion chamber burns once ignited. In both cases, the hot gases and particles are then accelerated and ejected to produce thrust. Recent years have seen the development of new bipropellant liquid oxygen (LOx)/Methane engines, including for future reusable launch vehicles. Fig. 1 shows the breakdown by propellants of the total annual number of successful orbital launches since 1957.

TABLE I: Common rocket propellants and examples of operational rockets using them or vehicles still in development (*). (X) indicates which stage(s) of the rocket use(s) that propellant, with (0) being the boosters. Stages three and above were not considered. [4, 10]

Propellants	Type	Rocket example
Liquid Oxygen (LOx) Liquid Hydrogen (LH_2)	Liquid	Ariane 5 ECA (1,2), Ariane 6* (1,2), Atlas V (2), Delta IV Heavy (0,1,2), H-IIA/IIB (1,2), New Glenn* (2), SLS* (1,2), Vulcan* (2)
Liquid Oxygen (LOx) Kerosene (RP-1)	Liquid	Atlas V (1), Electron (1,2), Falcon 9/Heavy (0,1,2), Long March 6/7(0,1,2), Soyuz 2 (0,1,2)
Nitrogen Tetroxide (N_2O_4) UDMH ± Hydrazine (N_2H_4)	Liquid	Long March 2/3/4 (0,1,2), Proton (1,2), PSLV (2)
Liquid Oxygen (LOx) Methane (CH_4)	Liquid	New Glenn* (1), Starship* (1,2), Vulcan* (1)
Ammonium Perchlorate (NH_4ClO_4) Aluminum (Al) ± PBAN or HTPB	Solid	Ariane 5 ECA (0), Ariane 6* (0), Atlas V (0), H-IIA/IIB (1,2), PSLV (0,1), SLS* (0), Vulcan* (0)

Combustion products emitted in the atmosphere also depend on the characteristics of the engines. In a bipropellant engine, the ratio of oxidizer to fuel (also called mixture ratio) influences the proportions of products in the exhaust flow—engines usually run fuel-rich to increase their efficiency [14]. These products can decompose into simpler constituents during combustion before recombining into different compounds. Finally, once ejected from the engine, the exhaust plume will mix with the ambient air, which can lead to afterburning of the remaining fuel and new reactions with the molecules present in the atmosphere at this altitude [15]. Therefore, the impact of rocket emissions depends on complex plume chemistry, which is still an active research area today. In the next section, Table II presents the main combustion products of each propellant and their potential impact when emitted in the higher atmosphere.

Rocket staging and launch profiles

Launch vehicles rely on staging to increase their efficiency: most rockets have between two and four stages that are largely independent and can rely on different propellants and engines. A first stage is ignited on the launchpad, will consume almost all of its propellant during ascent, and then will be jettisoned before the next stage is ignited. The last stage contains the payload and fairings. In addition, boosters can be attached to the first stage as an additional source of thrust. SRM propulsion is mostly used for boosters and some last stages, while liquid propulsion is standard for the first and second stages. The boosters and lower stages will return to Earth's surface and fall into the sea, or may land propulsively if they are reusable. Upper stages, which often have achieved high-enough speed to stay in orbit around the Earth for some time, usually end up reentering the atmosphere where they partially decompose (Fig. 2).

Mission performance, cost, and reliability have historically been the key drivers of rocket design. Sustainability is, at best, a secondary consideration in the launch vehicle market today. However, design choices—especially engine architecture and propellants—can induce radically different impacts on the environment, as shown in the next section.

The environmental impact of rocket launches

During the space shuttle era, researchers have started studying the environmental consequences of rockets, but today many questions remain unanswered [4, 16]. To date, researchers have measured and modeled exhaust from a handful of rockets and estimated some of their interactions with atmospheric chemistry [17, 18]. These interactions can be divided into i) local effects, including changes near launch sites, and ii) global effects, referring to the behavior of rocket exhaust at higher altitudes (see Fig. 2) [4, 6, 16].

TABLE II: Common rocket propellants, their main combustion products, and key identified environmental impacts. The volumes of combustion products emitted vary significantly by launch vehicle. Several exhaust products have the same type of environmental consequences, but not severity. Chemicals: water (H_2O), dihydrogen (H_2), hydroxide (OH), nitric oxides (NO_x), carbon oxides (CO_x), hydrochloric acid (HCl), dinitrogen (N_2), aluminum oxides (Al_xO_x) [4, 19]

Propellants	Main products	Global atmospheric impacts identified
Liquid Oxygen (LOx) Liquid Hydrogen (LH_2)	H_2O, H_2, OH, NO	Cloud formation
Liquid Oxygen (LOx) Kerosene (RP-1)	CO_2, H_2O, CO_x, OH, NO_x, soot	Ozone changes Radiative forcing Cloud formation
Nitrogen Tetroxide (N_2O_4) UDMH ± Hydrazine (N_2H_4)	H_2O, N_2, CO_2, NO_x, soot	Ozone changes Radiative forcing Cloud formation
Liquid Oxygen (LOx) Methane (CH_4)	H_2O, CO_2, CO, NO	Radiative forcing Cloud formation
Ammonium Perchlorate (NH_4ClO_4) Aluminum (Al) ± PBAN or HTPB	HCl, H_2O, CO_x, NOx, Al_2O_3, soot	Ozone changes Radiative forcing Cloud formation

Local environmental consequences

At launch sites, rockets create low-lying exhaust, known as a ground cloud, which interacts with nearby ecosystems, leading to measurable environmental changes. During shuttle launches, solid rocket motors emitted hydrochloric acid which collected in nearby lagoons and acidified the water, leading to abrupt, moderate fish kills [4, 16]. The 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 [20]. These areas of plant loss eventually recovered, although some species were replaced by weeds and more sensitive species failed to regrow [20]. Similarly, scientists in China measured decreases in insect abundance and biodiversity in two nearby tropical plantations after a Long March 7 launch [21, 22]. It was suggested that rocket launches at low frequencies are not likely a threat to local plant and insect populations, but increases in launch frequency could disrupt their recovery and lead to lasting consequences to the habitat's food chain [20, 22].

In addition to altering flora and fauna, rocket ground clouds can react chemically with nearby air before dispersing. However, this tropospheric rocket exhaust is generally thought to have transient effects and is otherwise assumed insignificant in the greater troposphere layer [3, 23, 24]. In the stratosphere, some 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 [18]. Other studies show that the Ariane V rocket creates a launch site ozone hole for approximately four days [25]. The exact environmental consequences of these local ozone holes are not well understood.

Besides gas emissions, spent rocket stages are often dropped over land and water, and can create toxic fuel leaks and impact craters. In central Kazakhstan, the Russian Proton rocket stages left traces of a carcinogenic fuel, unsymmetrical dimethylhydrazine (UDMH), causing ecosystem damage [26, 27]. The removal of UDMH from the environment via natural process remains debated, with some field experiments indicating rapid removal and other UN studies suggesting UDMH can persist in soil for at least 37 years [4, 27]. In any case, UDMH is a toxic substance harmful to persons interacting with crash sites [4]. Unsuccessful rocket launches can also expose the local environment to propellant spills, fires, and ecological damage [28].

Global environmental consequences

Successful rockets quickly ascend to higher altitudes and emit significant volumes of exhaust in the stratosphere, mesosphere, and higher [24, 29]. This exhaust disperses around the globe and can perturb Earth's atmosphere, including the climate system [3, 6, 24].

Stratospheric ozone depletion Rockets emit several substances that participate in ozone chemistry, namely hydrochloric acid and other forms of chlorine, water, hydrogen

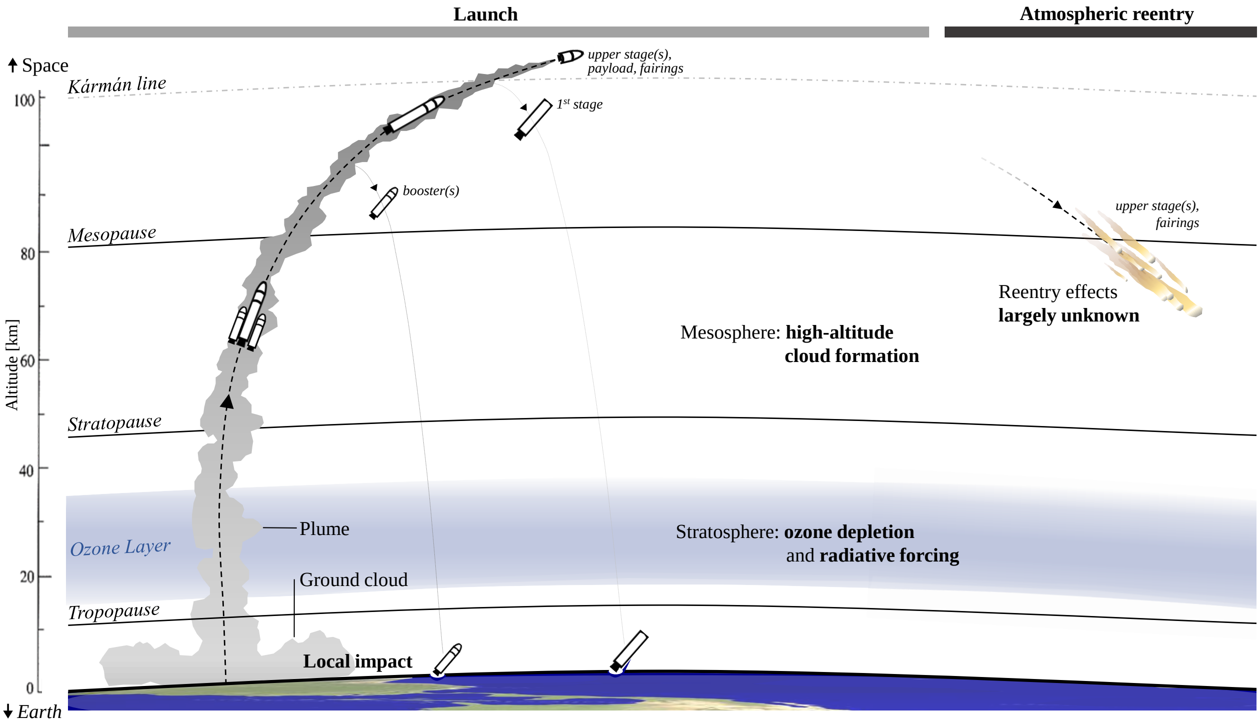

Figure 2: Trajectory of a typical launch vehicle through atmospheric layers during the ascent phase and the atmospheric reentry, with corresponding environmental impacts. The altitude of the various atmospheric layers is indicative and varies with the latitude. Objects are not to scale. Unless the rocket is (partially) reusable, the first stage and boosters are generally discarded in the ocean or on land. Environmental consequences shown above stem from various launch vehicles investigated in the literature.

gas, nitrogen oxides, hydroxide, alumina, and soot. Other rocket emissions such as carbon dioxide and carbon monoxide can indirectly affect ozone concentrations by cooling the stratosphere, slowing chemical reactions and ozone loss [30]. One study estimated that rocket launches in 2009 depleted approximately 0.03% of global ozone, a small amount compared to other ozone depletion species, such as chlorofluorocarbons [5]. However, the impact of rocket launch emissions on ozone depletion are expected to become more significant as the global launch rate and removal of more potent ozone depleters increases [5].

Solid rocket motors emit many forms of chlorine that can fuel ozone destruction [31]. Chlorine is a particularly efficient ozone depleter because, in addition to destroying ozone, it creates the necessary molecules to repeat and perpetuate the cycle [32]. As a result, chlorine emissions are typically considered one of the most serious SRM pollutants [31].

Compounding the harmful effects of chlorine, rocket-emitted alumina provides a catalytic surface for chlorine-based chemistry that depletes ozone. One study evaluated nine shuttle and six Titan IV launches and found that rocket-emitted alumina in the presence of background chlorine increased the rocket fleet's ozone depletion by 22% [31]. Moreover, alumina particles are efficient ozone depleters per unit mass emitted, meaning an accumulation of alumina could lead to higher levels of ozone depletion [31]. Alumina can have up to a two-year lifespan in the stratosphere and can accumulate with an increase in the number of launches [17, 31].

In contrast, rocket-emitted water and nitrogen oxides are not important ozone depleters, even though these products are always produced during launch. One study found that water and nitrogen oxides produced from 10 annual Proton launches (burning UDMH) reduced global ozone by less than 0.001% [33]. Moreover, the effect of water and nitrogen oxides on ozone likely remains small even as launch rates scale to significantly higher rates, and thus these emissions are of little environmental concern [3, 34].

Ice nucleation and high-altitude cloud formation A secondary effect of rocket emissions is an increase in cloudiness, especially in the stratosphere and mesosphere, where clouds are uncommon [3]. These high-altitude clouds typically form in polar regions during extremely cold conditions [35]. In otherwise extremely dry air, rocket-emitted water can supply the necessary ice molecules to grow clouds [35]. Increases in rocket launches and a shift towards fuels that emit more water vapor (such as methane and hydrogen) could significantly change high-altitude cloudiness. The Skylon space plane study with 100,000 launches per year found that cloudiness in the lower stratosphere and mesopause was predicted to increase as much as 20% [34]. While present-day launch rates are significantly lower than 100,000 launches per year, a single space shuttle launch created several clouds, accounting for 22% of the normal polar mesospheric cloud mass over the season [36]. Some experts suggest that this additional cloudiness could interfere with satellite communications, causing temporary disruptions [24].

Radiative forcing and climate change Rocket emissions inject gases and fine solid particles that interact with sunlight and Earth's natural infrared radiation [6]. These particles and gases can trap heat in the atmosphere and block incoming sunlight, providing shade [3]. With some particles able to remain in the stratosphere for three to five years, these particles can accumulate and form "umbrella"-like layers that warm or cool the planet, contributing to climate change [3, 37]. This effect is known as radiative forcing (RF). Positive RF indicates a warming effect, while negative RF indicates a cooling effect.

Black carbon, or soot, heats the stratosphere but cools the troposphere with an overall positive RF [6]. Similarly, alumina particles have a net positive RF [6]. In contrast, rocket-emitted carbon dioxide and water have insignificant RF contributions at present-day levels, and at significantly higher launch rates [6, 34]. In fact, studies show that black carbon is 100,000 times more effective at heating the atmosphere than rocket-emitted carbon dioxide [3, 6]. This finding is important since carbon dioxide is a well-known greenhouse gas and often the key problematic emission in other industries.

Overall, present-day rocket RF is small, approximately 0.008% of global, industry-wide carbon dioxide RF [6]. However, if rocket launch rates increase to 1000 launches per year (from 150–200 per year in 2022), rockets could produce similar amounts of positive RF as subsonic aviation [38].

Research gaps Many open questions remain about the environmental effects of rocket emissions. In nearly every article referenced in this section, authors highlighted the strong need for additional research and the limitations of current models. Some newly developed rocket propellants, like LOx/Methane, have yet to be studied in detail and may have markedly different emission characteristics and effects than previously studied propellants [3]. Overall, better data on rocket combustion products, emission interactions, and plume characteristics is needed to tune atmospheric models and validate results [6, 24, 33]. High altitude cloud formation and their radio interference and potential mitigation solutions also remain open areas of research [4, 24]. Furthermore, little research has been published on the environmental consequences of rocket disposal, including the melting of upper rocket stages as they reenter the atmosphere from space [39]. These metal particles may be warming or cooling the atmosphere and consequently a form of geoengineering with poorly understood global effects. While beyond the scope of this paper, the land, water, and atmospheric toll of manufacturing rockets and their propellants should also be explored to understand the complete environmental cost of operating rockets [40]. With a better idea of the environmental cost of rocket life cycles, metrics to quantify the sustainability of rocket designs and technology to enable greener propellants will help move the space launch industry towards more sustainable launchers.

Existing policies, regulatory challenges

Like other sources of atmospheric emissions, rocket emissions are not contained by national borders, which motivates the need for international coordination to effectively regulate them. To date, there is no international policy that directly addresses their impact. However, two existing treaties, the Montreal Protocol and the Paris Agreement, can be examined for their applicability to rocket emissions to understand what challenges and opportunities for regulation may exist.

The legally-binding Montreal Protocol has been highly effective at reducing ozone-depleting compounds in the atmosphere, despite being enacted without a unanimous scientific consensus about the impacts and level of mitigation needed [41]. Currently, its application to rocket emissions is limited as it is geared towards ozone-depleting compounds emitted on the ground [3]. However, there is precedent for the treaty to address issues that go beyond its original scope. In 2016, the Kigali Amendment to the Montreal Protocol was enacted to reduce the emission of hydrofluorocarbons—compounds which are powerful greenhouse gases but have limited impact on ozone.

The Paris Agreement is an international treaty on climate change that was adopted in 2015 and primarily tackles the emission of greenhouse gases. Unlike the Kyoto Protocol that preceded it, each country's emissions targets under the Paris Agreement are not legally binding but are instead voluntary and nationally determined. This would leave the possibility for countries to individually decide to address rocket launches as a growing source of greenhouse gas emissions under their nationally determined targets. Although rocket launches are not specifically addressed by the Paris Agreement, the issue of international aviation and shipping which release emissions outside national borders provides analogous issues to examine. Enacting policies to mitigate greenhouse emissions from international shipping and aviation are the responsibilities of the International Maritime Organization and the International Civil Aviation Organization, respectively. Recent external assessments have proposed that the responsibility for international shipping emissions should fall to the country of the ship owner [42]. This approach could potentially be viable for launch vehicles as well. However, the fact that rocket launch emissions occur both above and below the Kármán line that delineates space may be another regulatory challenge.

At national and local levels, there are few policies regulating the local environmental impacts of space launches. In France, following the French Space Operations Act (FSOA), a 2009 decree requires space vehicle operators to undergo an environmental assessment prior to receiving authorization to launch (2). In the U.S.—which in 2020 accounted for $\sim 40\%$ of global space launches—existing policies are limited to the general mandates of the Environmental Protection Agency (EPA), which requires assessment of all emissions sources and compliance with the standards of the Clean Air Act, and the Federal Aviation Administration (FAA), which requires launch vehicles and spaceports to undertake an environmental review before they receive a license to operate [10]. The EPA sets emissions standards for atmospheric pollutants based on whether the source is stationary or mobile, with the mobile classification being associated with less stringent standards. Previous determinations by the EPA have classified rocket launches as mobile sources, and no rulings have been made about the specific pollutant standards which apply to rocket engines [43].

Recent filings for the licensing of SpaceX's Starship/Super Heavy launches reflect a lack of standardized assessment methods, and the position of U.S. regulatory agencies and industry that the global atmospheric impact of space launches remains negligible. The programmatic environmental assessment notes that there are no established methods supported by the FAA to evaluate the significance of greenhouse gas emissions from rocket launches. The filings also estimated the volume of carbon dioxide emissions generated by five launches and noted that it is "significantly less" than the total U.S. annual greenhouse gas emissions [19]. As the U.S. is currently the second largest emitter of greenhouse gases globally and space launches still represent a small industry, this points to the lack of appropriate elements of comparison to assess either the relative or absolute future impact of rocket launches [44].

Rocket emissions fall into a category of environmental issues that are particularly difficult to regulate for several reasons summarized below.

The absence of standardized metrics

To quantitatively evaluate the individual and cumulative impacts of different launch vehicles, specific indicators dedicated to launch and reentry emissions would need to be developed and linked with environmental variables. As described previously, evaluating emissions based only on existing metrics such as carbon dioxide equivalents may underestimate or mischaracterize the true impact [6].

The lack of critical impacts to date

As the lack of nationally determined emissions targets that have been met under the Paris Agreement illustrates, even once a scientific consensus about harmful effects of atmospheric emissions has been established, translating scientific understanding into policy to mitigate those emissions can remain a challenge. To be actionable, scientific understanding should be presented in a way that is credible, salient, and legitimate to policymakers [45]. Currently, evaluations of the impact from rocket launch and reentry lack a critical mass of credible scientific assessments and regulatory agencies have been operating under the premise that rocket emissions pose an acceptable or negligible environmental risk [3]. This perception of the risk as negligible is not based on an assessment that all aspects of rocket emissions are fundamentally harmless in the atmosphere, but rather that they are small by volume, particularly compared to emissions from other sources. This assessment does not account for the future growth in launches, nor for the increasing difficulty of regulating an industry when design choices are already widely adopted before a comparative environmental assessment could be conducted.

The strategic nature of the launch industry

From the very beginning, space launch capabilities have been strategic for nations' military and ideological agendas. They are now also critical for economic purposes. Although not prohibitive to the initiation of voluntary international talks as there are precedents on nuclear matters, this context is not favorable to the implementation of effective measures that could be seen as threatening a country's access to space.

The atmosphere as a global commons

The atmosphere is a global commons, where emissions produced locally mix beyond national borders, and widespread impacts are the result of collective actions. Even with sufficient political will at a national level to regulate rocket emissions, widespread international participation is critical to maintaining a global commons.

Ways forward

In the context of a growing commitment towards sustainability for all human activities, the space launch industry is facing important challenges (3). A significant increase in atmospheric emissions from space launches is expected, while the levels of preparedness and societal response (including academic research, policymaking, and industry engagement) are still low. The path forward will be primarily defined by the nature of the solutions available to reduce the impact while developing the sector, and alternative ways to enforce these solutions effectively.

Mitigating the impact

The design of launch vehicles has been consistently driven by mission performance, cost, and reliability. For a design shift to occur that favors launch vehicles with reduced emissions, environmental impact and sustainability will have to become key considerations in rocket design and manufacturing. The diversity in rockets' environmental impacts—resulting from their diversity in designs—demonstrates that there are possible trade-offs between emissions and other considerations, particularly regarding propellants. SRMs' harmful emissions of chlorine and alumina particles should lead to a reduced role of these boosters in the architecture of future launchers. LOx/Kerosene engines, for their emission of soot particles and their radiative forcing effect, could also be challenged. LOx/Methane engines present advantages in that regard. However, the significant mass and launch frequency announced for the corresponding rockets represent a considerable step from current levels, and the overall impact will highly depend on life cycle aspects (ground operations with methane and its production).

Efforts to fill the existing research gaps will help inform and refine the relative merits of these design choices. That is why starting funded research initiatives on rocket emissions should be among the immediate priorities, to gather data from *in situ* measurements and develop methodologies. Life cycle assessments (LCAs), a recently-adopted practice in the space industry, have begun to emerge primarily in Europe as a suitable method to improve the environmental performance of launch vehicles [46]. Using LCAs helps to avoid typical burden-shifting phenomena as they allow for accounting all impacts from the drawing board until the launch and disposal (or reuse) of the systems.

Policy alternatives and perspectives

Although individual initiatives from single countries and manufacturers will be valuable to lead and develop frameworks, effectively addressing launch emissions will require global action. These measures can include regulatory alternatives as well as market-based solutions.

Regulation The increasing level of environmental awareness combined with the renewed exposure of the launch industry may increase the salience of launch emissions as an environmental issue, making regulatory efforts plausible. Regulatory approaches could also benefit from the existing diplomatic and scientific networks developed around climate action. Comparing the outcomes of the Montreal Protocol and the Paris Agreement suggests that the current lack of scientific evidence should not prevent discussions from beginning, to identify viable solutions for all stakeholders. Various regulatory tools can then be considered for their effectiveness and applicability. Taxes on rocket emissions, which would be a function of the purpose (i.e. tourism, science) of the launch, have been discussed (2). However, these may be difficult to implement as space missions are often multipurpose. In addition, negative economic effects could follow where enforced. Bans on specific types of propellants could also be considered as part of the licensing process for launches. This may prove challenging to implement at a global scale and may benefit from discussion about incentivizing the development or transfer of alternative designs, as the entire launch industry in some countries relies heavily on specific engine technologies and propellants. On a related issue concerning in-space propulsion, in 2022, the UN adopted a provision to phase out mercury (heavy metal highly toxic to humans) out of concern that it would then return to Earth's surface [47].

Market-based solutions Methods to frame environmental performance as a competitive advantage in the launch services market can help incentivize manufacturers to opt for sustainable designs. The development of a sustainability index for launch vehicles, as part of a multilateral cooperation between scientists, engineers, and companies willing to collect and share their data, could be instrumental for this purpose. This index should include measurable metrics on all relevant phases of the rocket's life cycle, not restricted to atmospheric emissions. This solution could lead to a purely market-based approach, but also be a basis for future international regulations. Cap-and-trade policies constitute another market-based option, where emissions would be limited by company or country, and could be traded, similarly to the European Union's Emissions Trading System which has been in use since 2005.

Conclusion

The space launch industry is expected to grow significantly over the next decade, and its environmental impact may also increase substantially if nothing is done to mitigate it. This impact is multiform, from local effects of pollution seen near the launchpads to global atmospheric impacts due to stratospheric and mesospheric emissions. There is currently no international regulation effectively addressing rocket emissions, mainly due to the perception of this impact as being minor. Research on the matter is urgent and critical to inform future policies. Considering that rocket emissions are highly dependent on design choices made about the launch vehicle (at the forefront of which are the propellant choice and rocket engine), incentivizing launch vehicle manufacturers to adopt more environmentally sustainable designs has the potential to be effective. The development of international policies or market-based solutions focused on life cycle sustainability could be considered. It will, however, be challenging to implement global measures as the issue tackles the protection of a global commons—the atmosphere—and still lacks public awareness. This is a critical time for implementing policy solutions, as technological choices made today will define the impact of the future fleet of launch vehicles. International discussions on this matter can already be started among countries, agencies, industry representatives, and scientists, concurrently with advancing scientific research on the topic.

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