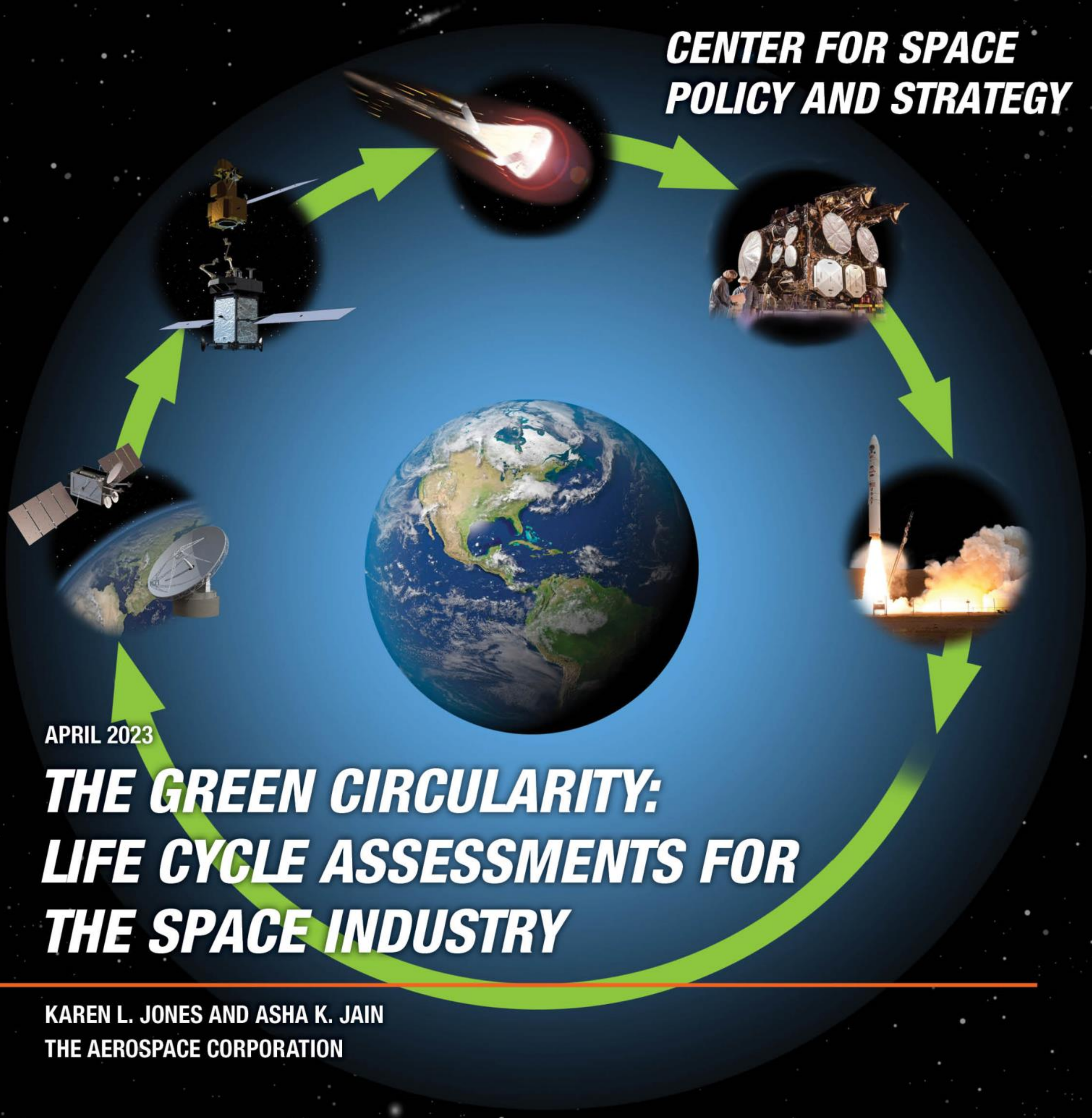

CENTER FOR SPACE POLICY AND STRATEGY

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THE GREEN CIRCULARITY: LIFE CYCLE ASSESSMENTS FOR THE SPACE INDUSTRY

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Summary

The rapid growth of the global space industry opens the door to an increasing volume and variety of space activities at the same time that companies are increasingly recognizing the value of environmentally responsible business practices. The environmental impacts of space activities are particularly challenging to understand and address given their complexity and distribution across different domains and industries. Multiple key areas still suffer from a lack of research, leaving critical knowledge gaps. Environmental life cycle assessments (E-LCAs) are one tool that can be applied to understand the space sector's cradle-to-grave impacts across space and terrestrial environments. Specifically, an E-LCA can identify circular economy opportunities to reduce waste and pollution by quantifying the environmental impacts of space missions or systems over their entire life cycle.*

This paper provides an overview of environmental and sustainability trends and offers options for the U.S. government, and Department of Defense (DOD) in particular, to consider and adopt E-LCAs in space acquisitions. As both DOD and civilian spacefaring agencies seek reduced environmental footprints, E-LCAs can motivate the space industry to improve designs, practices, and realize operational and economic efficiencies.

Additionally, the U.S. government is in a strong position, as a large and influential buyer of space systems, to support the harmonization of E-LCA methodologies and frameworks with international partners. Such efforts could catalyze a sustainable space industry while building transparency and trust for all stakeholders.

Introduction: Productive Harmony in Space and on Earth

In the United States and globally, there is growing pressure for every industry to account for their environmental impact and adopt sustainable practices. But the space industry has appeared at times to enjoy a "special status, a space exceptionalism which in turn is supported by and supports a space *exemptionalism*," meaning that the space industry views itself as different enough to be excused from typical environmental scrutiny and regulatory compliance expectations.[1] The issue goes

[*] "Life cycle" as a term is in a state of flux. ISO standardized this term as two words. However, in the United States, this term is still often a single word: "lifecycle."

beyond recent studies showing that implementation of space sustainability guidelines has been lagging.[2] The space community's view of sustainability in general has been limited, often focusing on impacts to the space environment without consideration of impacts on Earth and its atmosphere. Such a view is understandable given the historically low number of launches and orbiting satellites compared to the level of activity in other domains. But now this dynamic is changing as the volume and diversity of space activities grow. By the end of 2021, this figure had risen to 4,877.[3] Since the end of 2021 and through January of 2023, approximately 2,500 additional satellites have been launched, which raises the estimated number of active orbiting satellites to approximately 7,400. This unprecedented growth in space activity is now prompting greater scrutiny of the space industry's environmental impacts and potential to improve sustainability. On balance, the space sector contributes enormously to environmental and humanitarian concerns. Should the space sector continue to get a "free pass" to ignore its environmental footprint and sustainability opportunities?

Ultimately, "space exemptionalism" as national policy appears unlikely to persist indefinitely as the *United States Space Priorities Framework* (2021) now emphasizes U.S. leadership for "global governance of space activities" and "the development of new measures that contribute to the safety, stability, security, and long-term sustainability of space activities." The Framework also encourages "open, transparent, and international standards."[4] Furthermore, international agreements like the United Nations' Long-Term Sustainability (LTS) Guidelines, agreed to by nearly 100 countries including the United States, push for more comprehensive sustainability efforts throughout space activities.

One way to address sustainability goals is to examine mission or product lifecycles, cradle-to-grave, to reveal opportunities for environmental benefits as well as cost savings. The U.S. government could broadly meet the intent of the *Framework* by encouraging the standardization and application of environmental life cycle assessments (E-LCAs) for future government space systems or service acquisition efforts. E-LCAs can bring a diverse range of environmental impacts to light across all domains touched by space activities with an end goal of enabling measurable progress to improve space industry sustainability.

Industrial strategy in the United States and other nations is still forming in the era of climate change. Inevitably, there is a tension between the economic self-interests of a growing space sector and regulatory efforts to internalize negative externalities.[†] But there are options available to incorporate environmental policy considerations through government space stakeholders motivated by national interests.[5] Through leadership by example, the U.S. government has the opportunity to catalyze the space industry towards a more sustainable future.

Multi-domain Impacts: Space, Atmospheric, and Terrestrial

Sustainability has been an elusive and challenging goal for the space industry, partially because the meaning of the term *sustainability* depends upon context. The United Nations (UN) defines *space sustainability* as the "ability to maintain the conduct of space activities indefinitely into the future" and

[†] Negative externalities occur when activities undertaken to generate private benefit (e.g., profit) also produce costs on others that are not compensated.

the term is often used to refer to the worsening orbital debris situation. However, all space activities begin and many of them end on Earth; therefore, environmental sustainability from space activities should be viewed with a more expansive context. The Environmental Protection Agency (EPA) defines *sustainability* as the ability to "create and maintain conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations."[6] This broader EPA definition is central to this analysis and covers productive harmony in space *and* on Earth.

The space sector affects a wide range of operating environments and domains: the ground, sea, air, and space. The satellite industry's operations can generate a variety of environmental consequences, including stratospheric ozone depletion, air acidification, smog, toxic waste spills, water pollution, noise pollution, water consumption, and various types of material demands which can contribute to resource depletion.[7] These effects have varying severity, and in certain cases, are small but growing compared to other industries.[‡] Space players must navigate a complex web of overlapping regulatory regimes across ground, water, air, and space (see Figure 1) and across a range of satellite life cycle phases, including manufacturing, launch, operations, and reentry (see Figure 2).

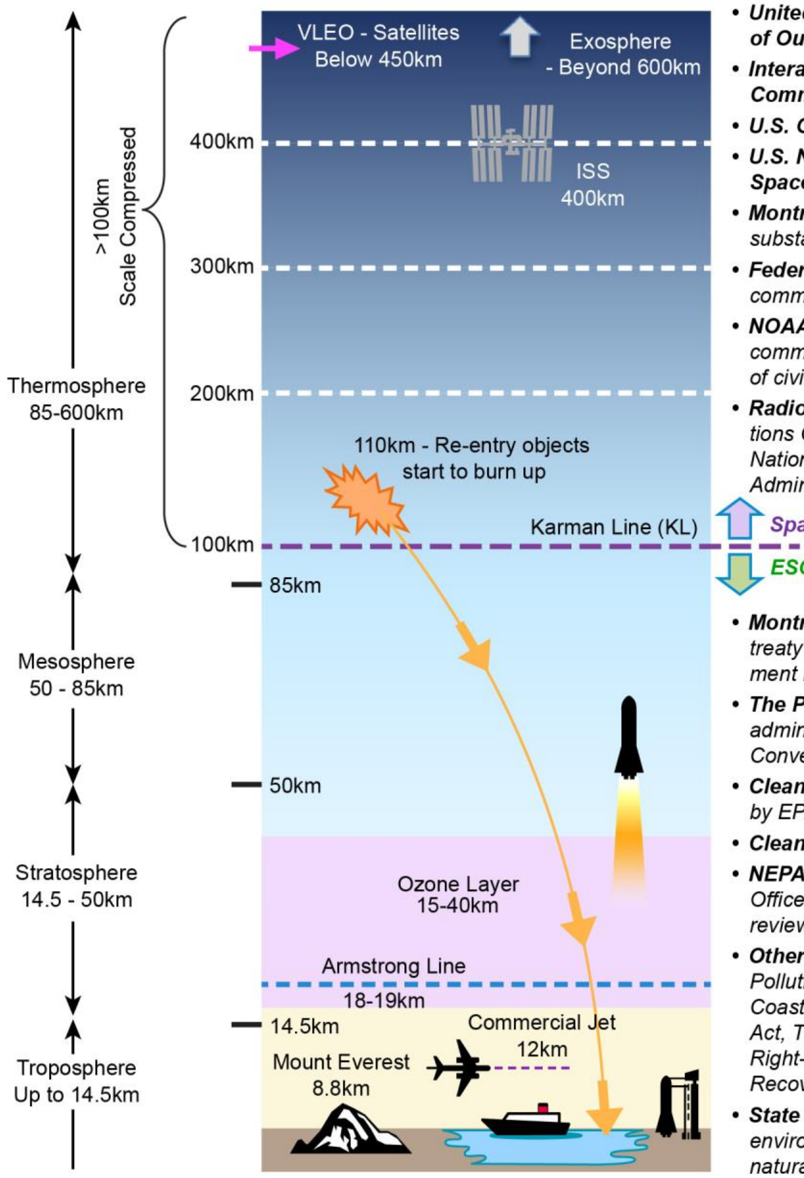
The border between space and Earth's atmosphere is commonly, but not universally, recognized at the Karman line, or 100 kilometers in altitude above mean sea level.[§] Above the Karman line, sustainability issues typically focus on space debris in crowded orbits, planetary protection on interplanetary missions, and to a growing extent electromagnetic spectrum interference issues. Below the Karman line, sustainability typically encompasses issues relating to Earth's natural resources, habitat, biodiversity, toxicity exposure, and pollution concerns.

The National Environmental Policy Act (NEPA) of 1969, 42 U.S.C. § 4332(C)

NEPA requires that federal agencies prepare a detailed environmental impact statement on federal actions and proposed mitigation measures to avoid adverse environmental impacts. The Federal Aviation Administration (FAA) Office of Commercial Space Transportation (AST) has been responsible for integrating environmental guidelines into its decisionmaking process and analyzing the environmental impacts of proposed and existing spaceports. For spaceports, the decision to license is a major federal action under NEPA, and therefore private sector spaceport siting, construction, and operation falls under NEPA.

The Karman line does not, however, reliably signal regulatory applicability. For instance, an Aerospace study noted that optical reflective emissions of orbiting satellites "may have a negative impact" on astronomical research from ground-based telescopes, a potential terrestrial impact from light pollution, but satellites appear to be exempt from the National Environmental Policy Act (NEPA).[8] At the

[‡] The space industry is several orders of magnitude smaller compared to other industries in terms of transportation volume. During 2021, there were only 150 orbital launches. By comparison, the International Air Transport Association (IATA) estimates that the number of domestic and global airline flights worldwide to be 22.2 million in 2021.
[§] The Karman Line was established in the 1960s by the Fédération Aéronautique Internationale in honor of physicist Theodore von Kármán. There is some disagreement regarding the exact altitude where space exists.



Regulatory and Policy Environment

- ***United Nations Committee on the Peaceful Uses of Outer Space***
- ***Interagency Space Debris Coordination Committee***
- ***U.S. Orbital Debris Mitigation Standard Practices***
- ***U.S. National Space Traffic Management Policy, Space Policy Directive-3***
- ***Montreal Protocol*** *- phase out ozone depleting substances.*
- ***Federal Aviation Administration*** *- regulates commercial launch and re-entry.*
- ***NOAA Office of Space Commerce*** *- licensing commercial remote sensing systems, development of civil space traffic mgt. Capabilities.*
- ***Radio Frequency Spectrum*** *- Federal Communications Commission regulates non-federal use; National Telecommunications and Information Administration regulates federal use.*

Space Sustainability Ratings *- Typical above KL*

ESG Ratings *- Typical below KL*

- ***Montreal Protocol*** *- Ozone Protection, international treaty administered by the United Nations Environment Program.*
- ***The Paris Agreement*** *- international treaty, administered by United Nations Framework Convention on Climate Change.*
- ***Clean Air Act*** *- focus on criterial pollutants, admin by EPA.*
- ***Clean Water Act*** *- administered by EPA.*
- ***NEPA*** *- focus on mitigation due to federal actions, Office of Federal Activities coordinates EPA's review.*
- ***Other*** *- Executive Order on Environmental Justice, Pollution Prevention Act, Endangered Species Act, Coastal Zone Management Act, Wetlands Protection Act, The Emergency Planning & Community Right-to-Know Act, Resource Conservation and Recovery Act.*
- ***State & Local Regulations*** *- to protect people, environment, cultural, historical, recreational and natural resources.*

Figure 1: The space industry's complex multi-domain environment. *Traversing different geographies and physical boundaries, space requires an understanding of national, regional, and international regulations and norms of behavior to address impacts above the Karman line, in the atmosphere, and in the terrestrial ecosystems and communities.*[9]

same time, spaceport licensing is subject to NEPA review (see sidebar) and terrestrial industrial activities relating to rocket production, launch, and satellite manufacturing are subject to a range of federal and state environmental regulations (see Figure 1).

Above Karman Line: Space Sustainability

In response to the growing debris problem in space, the United Nations, national space agencies, space industry associations, and various regulatory agencies, such as the Federal Communications Commission (FCC), have collaborated to develop and demonstrate best practices for space sustainability.[10] The U.S. Government Orbital Debris Mitigation Standard Practices (ODMSP), established in 2000, applies to U.S. organizations involved in space operations and is considered the foundation for national orbital debris mitigation requirements and guidance. More recently, Space Policy Directive-3 and the 2020 National Space Policy call for U.S. leadership and international industry standards to address space traffic management, preserve a sustainable space environment, and work towards a safer space operations environment. Additionally, a member of Congress has introduced legislation to address concerns about the fiscal and environmental sustainability of space activities.[11] Beyond domestic U.S. policies, there are multilateral efforts underway led by the Inter-Agency Space Debris Coordination Committee (IADC) and the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS).[12] To further motivate the industry towards sustainable practices, several organizations, catalyzed by the World Economic Forum,[**] have worked together to develop Space Sustainability Ratings (SSR).[13] Similar to other consumer information ratings, like Leadership in Energy and Environmental Design (LEED), the SSR provides a technical standard to give space operators a common sustainability assessment framework to enhance environmental transparency.[14] Members of the SSR design team, Danielle Wood and Minoo Rathnasabapathy, noted that "space operators are feeling positive pressure to demonstrate their commitment to space sustainability and do not want to be the 'last one in.'"[15] Thus far, the SSR addresses the space environment, above the Karman line.

Below Karman Line: Environmental Impacts

Like other industries, space is regulated by state, federal, and international laws governing air, water, and land use. Space actors are required to comply with both procedural and regulatory requirements across the space industry value chain,[††] including manufacturing, operations, and launch facilities. Depending upon the industrial process and location, a wide range of sustainability, procedural, and environmental regulations might apply.

Atmospheric Impacts

The satellite industry introduces a range of atmospheric impacts. According to Dr. Martin Ross, an Aerospace scientist who studies atmospheric impacts, "Spaceflight emissions are the only human-produced compounds injected into the atmosphere above 18 km." Ross emphasizes that, compared to aviation emissions, "black carbon from a rocket could introduce immediate and long-range consequences which are an order of magnitude higher."[16] Besides black carbon, other emissions are harmful to the atmosphere and have been targeted by international agreements. The Montreal Protocol,

[**] World Economic Forum, European Space Agency, Massachusetts Institute of Technology, Univ. of Texas, and BryceTech have worked to develop the SSR, which is currently being administered by Space Center at École Polytechnique Fédérale de Lausanne.

[††] The value chain implies the full chain of a business's activities in the creation of a space product or service.

an international treaty drafted in 1987 and which entered into force in 1989, successfully banned or limited nearly 100 substances that deplete the ozone layer, but the agreement does not address emission sources such as rockets and aircraft that emit directly into the stratosphere.[17]

Some launch providers are moving towards cleaner-burning rocket propellants, such as hydrogen and methane,[‡‡] and away from kerosene, hydrazine, and aluminum-based solid rocket fuels for both environmental and financial reasons (see sidebar). Kerosene, a highly enriched petroleum product, and hydrazine, a carcinogenic fuel, produce several by-products when burned, including carbon dioxide, black carbon, and water. Aluminum-based solid rocket motors typically produce chlorine gases, alumina, and carbon dioxide. Several studies have shown that black carbon, alumina, and chlorine emissions are among the most concerning rocket combustion products while rocket-produced carbon dioxide and water have negligible effects on the ozone layer and greenhouse gas effect. Cleaner burning fuels, like hydrogen and methane, produce no chlorine, alumina, or black carbon. Instead, hydrogen combustion creates only water, leading to less harmful atmospheric consequences for rocket launches. Moreover, methane combustion produces water and carbon dioxide, which is not associated with atmospheric warming in the upper atmosphere and, in fact, may have a cooling effect. This differs from the effect at lower altitudes where carbon dioxide behaves as a greenhouse gas, absorbing infrared radiation and heating the lower atmosphere.[18]

Removing Hydrazine in Launch and Satellite Propulsion

The trend towards methane and hydrogen propellants mirrors a decline in hydrazine use in rockets and satellites. Since the 1960s, hydrazine has been regularly used for spacecraft propulsion and control thrusters and rocket stages.[19] It is known to be highly toxic, carcinogenic, and corrosive, which makes it difficult and expensive to handle. A commercial contractor working with the European Space Agency (ESA) to test new propellants commented that the research was motivated primarily to keep the environment and the workforce safe from contamination, but added that "there are also financial gains from eliminating the infrastructure needed for handling toxic fuels, which would reduce the cost and cycle time of launching spacecraft."[20] In the end, shifting away from hydrazine and towards greener and safer propellants can eliminate certain health and safety risks while improving the corporate bottom line.[21] Despite hydrazine's decreasing popularity, particularly for rockets, China continues to use hydrazine for its older generation of CZ rockets and most recently for the fourth stage of the Ceres-1 launch vehicle.[22]

Atmospheric impacts occur during reentry as well as launch. When a satellite reaches end-of-life and deorbits, the high-temperature process of atmospheric reentry melts away approximately 60 to 90 percent of a reentering object, leaving behind metal particles in the upper atmosphere, known as particulates.[23] These particulates[§§] can remain suspended in the atmosphere for several years and

‡‡ Although methane is a potent greenhouse gas, it is a clean-burning fuel. If fugitive methane leaks could be avoided during extraction, propellant transport, and storage phases, then methane could be considered a clean rocket fuel from a life cycle perspective. In December 2022, China's Zhuque-2 attempted the first orbital launch of a methane-fueled rocket. Other next generation methane rockets might include SpaceX's Starship, the ULA Vulcan, Blue Origin's New Glenn, Rocket Lab's Neutron and Terran 1 from Relativity Space.

§§ Amount of particulates ablated during reentry depends upon mass, volume, and angle of reentry.

eventually scatter and settle on Earth's surface.[24] Especially as the scale of re-entries grows, these particulates could alter atmospheric behavior. Once lower in the atmosphere, some of these particulates, including alumina, can interact with ozone-depleting chemistry and alter global temperatures.[25] The annual number of objects launched into space has increased significantly since 1987 when the Montreal Protocol was drafted. In that year, 135 objects[***] were launched into space. More recently, during 2021, over 1,807 objects were launched into space. What goes up must eventually come down if it is not disposed in a graveyard orbit, and therefore the growing mass of objects in space portends a future higher rate of reentries, which will result in a rise in atmospheric particulates and therefore an increased likelihood of atmospheric impacts.[26]

Terrestrial Impacts

Terrestrial impacts from launch can be significant. Spaceports and launch sites require a large amount of land and can contribute to the destruction of critical habitats and biodiversity.[27] Over 367,000 acres in the United States are licensed as an FAA, federal, or private spaceport. Moreover, out of 17 licensed spaceports, nine are in coastal areas and their construction often requires the destruction of wetlands. Swamps, marshlands, and coastal areas are typically protected by a wide range of federal and state regulations because wetlands offer water quality protection, fish and wildlife habitats, natural floodwater storage and buffer, and reduction in the erosive potential of surface water.[28] In addition, for any development or construction impacts related to a spaceport, a range of environmental laws could apply to air quality, noise and compatible land use, light emissions, historical and cultural resources, protection of recreational lands and parks, water resources, and biological resources and habitats.

Life Cycle Assessments as a Path to the Circular Space Economy

There is often no standard or harmonized method to measure whether an industry has achieved sustainable consumption or production levels. For space activities, this is particularly challenging when both harmful impacts and mitigation measures span so many different contexts and domains. One way to synthesize a study of these complex dynamics is to develop a process for conducting environmental life cycle assessments (E-LCAs) for space activities, exploring the relationship between the activity and the environment at every stage of space system development, operation, and disposal. An E-LCA can be used to measure or validate environmental impacts, making it a potentially critical assessment tool as more industries strive for higher levels of long-term sustainability.[29]

E-LCAs can be useful beyond measuring the current impact of space activities. They can also establish milestones towards a key feature of sustainable industries, the "circular economy." According to the U.S. Environmental Protection Agency (EPA), a *circular economy*[†††] uses a systems-focused approach that is restorative or regenerative by design to enable resources to maintain their highest value for as long as possible.[30] In other words, circular economies eliminate waste through better process design across their life cycle. As industries transition from a traditional *linear economy*, or "*take-make-use and dispose*" practices, to a circular economy, or "*make-use-recycle and/or reuse,*" they

[***] Satellites, probes, landers, crewed spacecraft, and space station flight elements.
[†††] *Circular economy* principles are recognized by the United Nations Environment Assembly as key for achieving sustainable consumption and production patterns.

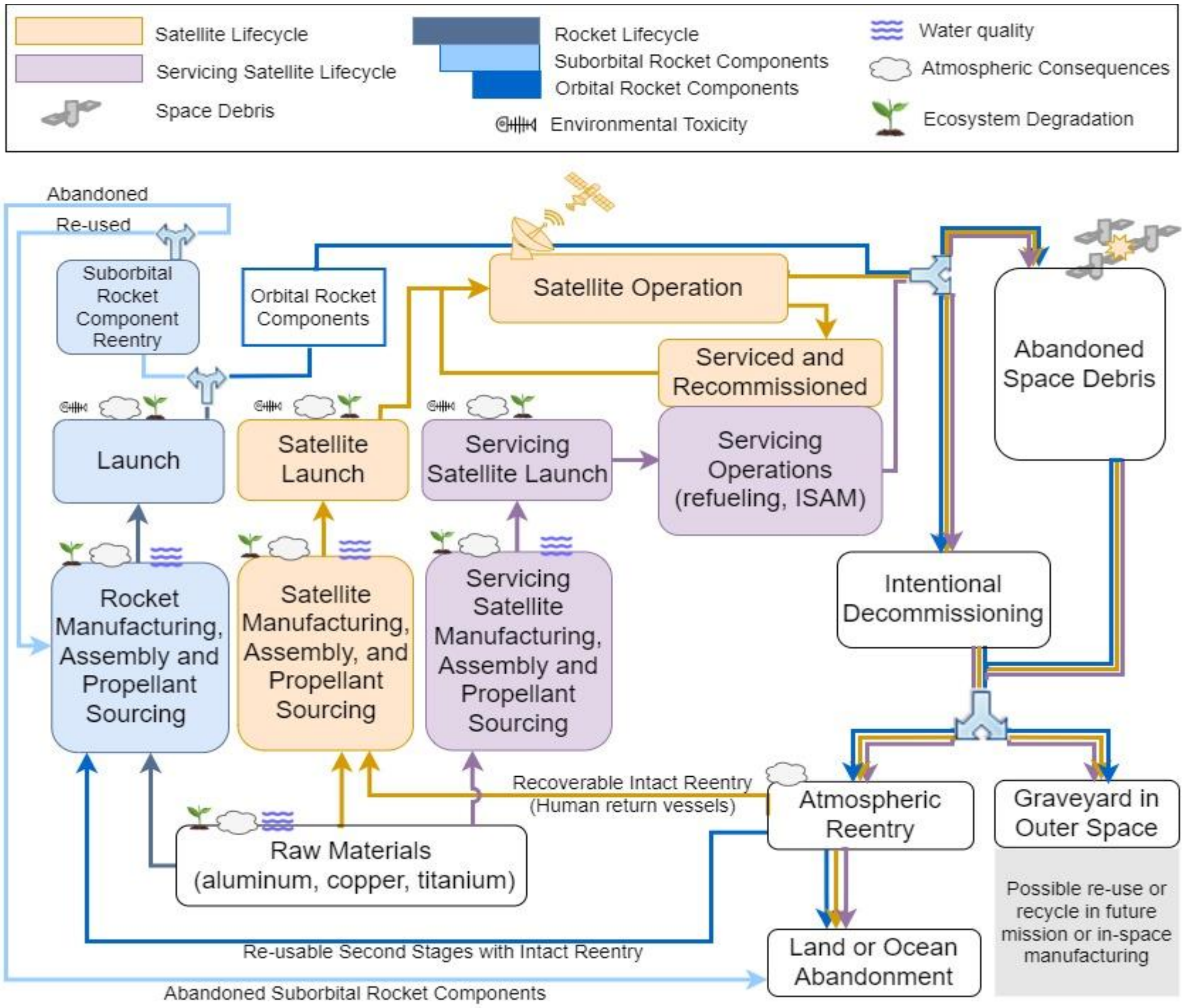


Figure 2 Satellite Life Cycle Overview.[31] *For rockets, satellites, and satellite servicing operations, the cradle-to-grave environmental impacts include consequences to water, atmosphere, ecosystems, workplace health and safety, and space (e.g., debris). The circular nature of the space industry across launch, satellite manufacturing and operations, and in-space servicing allows increased sustainability opportunities, wherein the materials or waste from one phase can "loop back" to provide re-use for future manufacturing or extended life missions.* Note*: System boundaries do not include raw material extractive processes or design processes.*

need a standardized way to measure and navigate toward more sustainable practices. Circular economy principles are gaining global momentum: 193 countries and the European Union are parties to the Paris Agreement, an international treaty on climate change.[32] According to the UN, engaging in circular economy principles is critical to meeting the terms of the Paris Agreement by avoiding the waste, emissions, and biodiversity loss caused by resource extraction and use.[33] With widespread adoption, E-LCAs offer a credible technical approach to fulfill these commitments and a path forward to a circular economy for space activities.

Like many industrial life cycles, the satellite life cycle is complex, with both tangible, observable effects and numerous unknown consequences. The system boundary of satellite life cycles, graphicly summarized in Figure 2 at a high level, is extended to the entire value chain or satellite economy. Mapping life cycles facilitates a broad consideration of the industry's extended supply chain, environmental impacts, and how one process can "loop back" and become an input for another process.

The Circular Economy: Life Cycles, Environmental Economics, and Natural Capital

Life cycle frameworks are not new: they stretch back well before the first UN Climate Change Conference in 1995. During the 1970s, life cycle assessments (LCAs) evolved from methodologies such as energy analysis and environmental burden analysis. Between 1970 and 1990, a variety of life cycle methodologies existed but without a common framework. Later, between years 1990 and 2000, various LCA guidebooks were published and eventually the International Organization for Standardization (ISO) standardized methods and procedures.

E-LCAs are not entirely new to the space industry. The European Space Agency (ESA) has been exploring the life cycle methodology for over a decade and, in 2009, ESA established a Clean Space office to address space industry environmental challenges. During the past few years, ESA has included E-LCA requirements in projects such as Copernicus and Ariane 6 expansion missions.[34]

ESA concluded that ISO standards 14040 and 14044 "are not sector specific and leave many options open for the LCA practitioner to decide."[35] ESA added that the space industry is quite different, with low production rates, long development cycles, specialized materials and processes, and unique operating environments in the high atmosphere.[36] To address the space industry's unique characteristics and operating environment, ESA published the *Space System Life Cycle Assessment (LCA) Guidelines* in 2016 to extend ISO 14040 and 14044 to the space sector. This framework includes five impact categories which ESA expects E-LCAs to specifically address:[‡‡‡]

- Ozone depletion
- Climate change
- Metal and mineral resource depletion
- Human toxicity
- Freshwater aquatic ecotoxicity

Following the establishment of life cycle assessments, the United Nations developed the

[‡‡‡] Various LCA methodologies apply different impact categories, such as: air acidification, particulate matter, photochemical oxidation, ionizing radiation, land use, etc.

System of Environmental Economic Accounts (SEEA) during 1993 as an international standard. SEEA is considered a crucial step to quantify the environment into national accounts. More recently, during January 2023, the White House issued the first ever U.S. *National Strategy to Develop Statistics for Environmental-Economic Decisions* ("National Strategy"). The National Strategy "creates a U.S. system to account for natural assets—from the minerals that power our tech economy and are driving the electric-vehicle revolution, to the ocean and rivers that support our fishing industry, to the forests that clean our air—and quantify the immense value this natural capital provides."[37] The National Strategy also recommends that the U.S. incorporate the internationally agreed-upon SEEA "to guide development of U.S. natural capital accounts and environmental-economic statistics, where the SEEA standards are relevant and robustly developed."

Life cycle assessments, SEEA, and natural capital accounting are all mutually supportive. Combined, they represent a fundamental shift in how our society and economy values the previously ignored and unquantified resources, recognizing that nature and natural resources are "capital assets that are critical for economic growth and prosperity, and that their inclusion in economic planning is imperative for addressing 21st century economic challenges such as climate change, biodiversity loss, and declines in natural capital wealth."[38]

Global Implications – Competition and U.S. Leadership

The complexities of international trade, cooperation, and competition will impact the costs and benefits of requiring and applying space related E-LCAs. For instance, ESA's lead with space life cycles presents an opportunity for the U.S. government to leverage lessons learned and to coordinate and harmonize methodologies. Conversely, if the U.S. government ignores or lags behind Europe in adopting life cycle methodology for the space industry, such inaction could imperil international trade relations. A significant portion of the U.S. space industry benefits from exports to other countries, especially to Europe. If LCAs become a mandatory reporting requirement for Europe, the U.S. could lose market share and U.S. satellite suppliers could be "cut-off by European consumers."[39]

There are also persistent concerns that burdensome regulations could cause U.S. industries to lose competitive advantage and lag behind China, referred to as "a very aggressive competitor" by NASA administrator Bill Nelson.[40] China appears to be unencumbered by many established norms of behavior in space, as evidenced by allowing their massive first stage rockets to fall uncontrollably back to Earth. However, there is good reason to believe that China has the will and resources to reach certain climate goals. China is working to redeem its negative environmental image and has launched several climate adaptation and resilience efforts, including a plan to decarbonize its highly industrialized economy by 2060 and a national strategy to protect wetlands, ecodiversity, and forested areas. In fact, the World Economic Forum notes that compared with Western market-driven models, China's authoritarian top-down economic planning approach may prove advantageous for long-term investing to respond to climate.[41] Regardless of economic policies or political structures, all industrialized countries face a challenging journey to a carbon-free and sustainable future. And now, the United States has an opportunity to lead and navigate using E-LCAs to help the global space industry adapt.

E-LCA adoption would also be a way to demonstrate U.S. space sustainability leadership and to implement the U.N. Guidelines for the Long-term Sustainability of Outer Space Activities of the Committee on the Peaceful Uses of Outer Space, emphasizing international responsibility for national activities in outer space to:

> "(b) Develop specific requirements and procedures to address the safety and reliability of outer space activities under the entity's control, during all phases of a mission life cycle;
>
> (c) Assess all risks to the long-term sustainability of outer space activities associated with the space activities conducted by the entity, in all phases of the mission life cycle, and take steps to mitigate such risks to the extent feasible."[42]

Approximately 100 COPUOS member states—which include the U.S. and China—could interpret that long-term sustainability risks would encompass environmental impacts to both the orbital and Earth environment, and that LTS guidelines call for an E-LCA or something like an E-LCA.

Challenges and Opportunities Across the Space Activity Value Chain

In general, E-LCAs can help close loops in the satellite industry life cycle to fuel a circular space economy. Table 1 offers an overview of satellite life cycle challenges during the phases of manufacturing, launch, operations, and decommission. Each of these challenges also presents opportunities to apply life cycle thinking to identify new means and methods for achieving cleaner and more sustainable practices.

Supply chain vulnerability is one area of concern, highlighted in the manufacturing section of Table 1. This issue has been underscored by events such as the COVID-19 pandemic and the Russian invasion of Ukraine. Most space companies are now striving to strengthen their supply chain and make it more valuable, agile, and resilient. Companies are now adding resource depletion metrics to the E-LCA process to position themselves for future supply chain constraints and unpredictable availability. These efforts could address important materials with vulnerable supply chains, such as titanium, a key metal for rocket bodies and space structures; lithium that is specially adapted for space satellite batteries; and germanium, a substrate for photovoltaic cells. For example, Russian titanium accounts for about a third of Boeing's titanium needs and about half of Airbus's supply, yet Russia has low levels of titanium mineral reserves.[43] Since the three largest suppliers of titanium are China, Japan, and Russia, this supply line has a higher geopolitical risk exposure, creating additional supply chain uncertainty. Beyond availability concerns, today's inflationary pressures have increased prices for many materials, which further underscores the need to reduce waste and consider more efficient practices throughout the satellite life cycle. Environmental life cycle analysis does not itself solve supply chain vulnerabilities, but the visibility needed to conduct them also supports supply chain risk mitigation efforts.

Table 1: Satellite Environmental Life Cycle	
Challenges	**Opportunities**
Manufacturing *Procuring raw materials, transporting materials and components, operating the manufacturing site, satellite assembly, and testing*	
• Supply chain delays and shortages, rare earth elements (REEs) and dependence upon uncertain foreign suppliers. • Material sources that can cause various adverse impacts to land, air, and water	• Explore supply chain risk mitigation strategies, such as REE substitution and diversifying supply base. • Selecting sustainable materials, including related extraction techniques. • Select less toxic supply chain materials for safer and less costly handling and manufacturing.
Launch *Rocket manufacturing, propellant sourcing, launch site operations and maintenance*	
• Terrestrial impacts of launch sites. • Rocket propellants, such as methane and kerosene, can have notable environmental footprints during extraction phase. • Potential for propellant leaks resulting in greenhouse gas (GHG) emissions. • Stratospheric ozone depletion from rocket combustion and resultant gases (e.g., HCl, NO_x) or particles (e.g., black carbon, AL_2O_3).	• Shifting to clean burning fuels during the launch phase, such as methane and low carbon hydrogen and away from kerosene, hydrazine, and aluminum-based solid rocket fuels. • Reusable rocket systems offering sustainability advantages in terms of resource efficiency as well as potential cost savings.
Satellite On-orbit Operations *Satellite operations including ground stations, network operations centers, and data or cloud services supported by data centers*	
• Ground stations located in environmentally sensitive areas. • RF Spectrum - satellites could interfere with radio frequencies supporting space operations, cell phone networks, radio towers, and other terrestrial services. • Debris – collision possibilities and the potential for dangerous debris clouds. • Data centers – energy-intensive data centers could increase carbon footprint.	• Minimize ground station footprints and avoid environmentally sensitive areas. • Use spectrum-efficient transmitters and receiver designs. • Debris – follow debris mitigation guidelines to limit debris, potential for break-ups, collisions, intentional destruction, stored energy at end-of-life, and the long-term presence of spacecraft in both LEO and GEO. • Data centers - renewable energy sourced.
End-of-Life/Decommission *Collision avoidance, reentry plans, move to graveyard orbit*	
• Continued on-orbit collision risks. • Stratospheric particle pollution from reentry, including aluminum oxide and black carbon. • Water and land consequences of debris abandonment, and risk to human life and property during uncontrolled reentry.	• Space situational awareness tools, simulations, and programs. • On-orbit servicing for refueling in-space repair and debris recycling to extend lifetime of satellite, including avoiding expensive replacement satellite. • Benign materials to reduce potential impact to ozone and upper stratosphere (more research needed).

The Art and Science of Environmental Life Cycles

Despite existing efforts and growing interest in life cycle assessments to achieve a circular economy for space activities, there is a long road ahead before widespread industry adoption of E-LCAs. Implementation of E-LCAs is both an art and a science, requiring balance among highly technical measurements, subjective judgment, and a need to clearly communicate the results to various audiences, as well as other factors.[44] The maturation path for E-LCAs in the space sector will involve a combination of improving access and data integrity, establishing metrics and standardized reporting, and addressing research gaps.

E-LCAs – Ensuring Integrity, Access, and Strategic Insight

According to Dr. Andrew Ross Wilson, University of Strathclyde, LCAs are still relatively new in the space sector and concerns about sharing potentially sensitive information play a role in hesitancy to implement. Wilson stated: "I'm not aware of many LCAs being done. Certainly, confidentiality is a big concern from industry." He added that space companies currently view life cycle inventory data as confidential, competition-sensitive information. This lack of willingness to share makes it very hard to populate space LCA databases and substantiate any environmental sustainability claims these companies may make.[45]

Fear of revealing proprietary or strategic information could be mitigated by an E-LCA process orchestrated by a trusted body with a data management protocol which provides both sufficient information to conduct E-LCAs and protection of confidential and competitive information. There is, for example, supply chain information that companies may never want to make public but would be willing to release to a trusted and responsible party for overseeing E-LCAs, with access strictly limited to E-LCA assessors.[§§§] At the same time, open data enable accountability, so companies would be encouraged to release as much information as possible, with any confidential data anonymized before being made public. Also, "open

Environmental Sustainability and Governance (ESG) Scores – Need for Methodology and Verification

Environmental sustainability and governance (ESG) scores complement and reinforce the need for E-LCAs because the financial industry is expecting greater application of ESG scores and E-LCAs can provide the analytical rigor to support greater transparency to fund managers and institutional or individual investors. The Gartner Group defines ESG as "a collection of corporate performance evaluation criteria that assess the robustness of a company's governance mechanisms and its ability to effectively manage its environmental and social impacts."[46] However, recent research suggests ESG scores are correlated with the quantity of voluntary disclosures rather than a company's compliance records or actual levels of carbon emissions.[47] This research supports a growing push for better ESG methodology and verification. Moreover, trusted third party E-LCAs could increase the rigor of ESG disclosures.

[§§§] Third party independent experts are normally required to review LCAs, particularly if followed by a published Product Environmental Footprint (PEF) or an Environmental Product Declaration (EPD). Programs such as Leadership in Energy and Environmental Design (LEED) buildings may soon introduce standards for environmental declarations that demand increased transparency and detail. And while more information could compromise proprietary technology, there are neutral parties who can guard such details. Confidentiality concerns are surfacing across a range of sectors dealing with environmental transparency and sustainability ratings.

data" can be protected with role-based access where only a subset of data would be made public (internationally or nationally), while the full set of data would be open to trusted E-LCA assessors. E-LCA data management, access, and security will need further consideration, based upon input from all stakeholders involved.

Metrics and Standardized Reporting for Objective Analysis

A crucial part of any life cycle data management plan is to standardize how data is reported to provide meaningful metrics and enable fair "apples-to-apples" comparisons.[48] Making sense out of any LCA should start with identifying functional units or reportable metrics.

Functional units are foundational to any life cycle assessment and enable objective comparisons across disparate products and technologies. LCA guidelines suggest that functional units should be: quantitative and precise; expressed in terms of application-specific performance requirements; and defined broadly enough to encompass competing technologies in the same functional unit definition.[49] Developing the most appropriate functional units is *not* an easy task and would involve deliberation across a range of constituencies, including the government space stakeholders, the commercial space sector, trade associations, and environmental regulators. One mistake would be to oversimplify industry metrics down to only one functional unit. Best practice is to consider use cases and market sectors, and to apply a range of functional units to specific products or applications.

In the case of established transport industries, for instance, the following metrics are used to analyze various aspects of transport impacts:

- Passenger kilometer of travel (PKM), representing the transport of one passenger
- Vehicle kilometer of travel (VKM), traffic flow, determined by multiplying the number of vehicles on a given road or traffic network by the average length of their trips
- Lifetime vehicle travel (LKM), total lifetime kilometers of a vehicle.[50]

What functional units should apply to LCA findings for the space sector? The sector does not enjoy a unified mission, such as transporting people from one location to the next. Instead, there are many missions, such as human spaceflight and tourism, communications, remote sensing, and navigation services. Since each mission delivers different types of products, the reportable metrics should reflect those products. For remote sensing this might include a measurement of environmental impact per pixel or, for satellite connectivity, a measurement of environmental impact per Mb transmitted. For the space tourism industry, this could include environmental impact per passenger trip or per hour of tourist flight.

Research Gaps Need to be Addressed

Further research in several understudied research areas could better inform the scientific community, space industry, and government on the environmental consequences of launching and operating satellites, especially given the differences among space missions. These areas include the atmospheric consequences of launch and reentry emissions, manufacturing and material sourcing processes, and local disturbances caused during launch and debris abandonment. Environmental studies could include in-situ measurements, such as rocket plumes in the stratosphere; long-term observations of the upper stratosphere to the lower mesosphere; and information on combustion products across rocket engine manufacturers. Better data and scientific understanding of these environmental processes will inform satellite life cycle assessments and contribute to creating a diversified database of industrial practices and their environmental consequences. This information will help industry identify areas of possible technological innovation and sustainability improvement while informing policymakers on tolerable practices and emission standards.

Climbing the LCA Learning Curve

Adoption of an E-LCA requirement could impose a significant implementation burden on space industry stakeholders. To help overcome early hurdles, the research community could work with regulators and industry to advance the knowledge base for E-LCAs, with the intent to close critical knowledge gaps. Regulators will also need to be comfortable with partial information because life cycle inventory data can be difficult to obtain, and best estimates will sometimes need to suffice. Also, the government acquisition process is already slow and burdensome; adding an additional E-LCA expectation could further delay an acquisition cycle. Regulators and acquiring agencies should also consider a phased approach with appropriate pilot activities to maximize learning and minimize disruption. As the life cycle discipline matures, government and the commercial space community can build a body of knowledge which, with time and practice, can reduce the implementation burden.

Beyond E-LCAs - A Range of Sustainability Transparency Tools Exist

E-LCAs are standardized and credible tools to assess environmental impacts associated with all the stages of a product or service life cycle. But there are other compelling methodologies that could apply to understand various impacts, each offering different advantages and limitations. First, not all E-LCAs are cradle-to-grave. Partial E-LCAs, such as "cradle-to-gate," do not include the operational use or disposal phases of a product or service. Also, depending upon needs and interests, metrics that address energy consumption, water usage, or waste and pollution could be useful. Other metrics and tools could include:

- Life Cycle Sustainability Assessment (LCSA) – a broad framework of models, including an E-LCA, to fully capture all three sustainability dimensions: environment, society, and economy.[51,52]
- Climate Risk Index – including how companies report transition risks and existing physical risks due to climate change.
- Carbon Return on Investment (CROI) – a narrower product than an E-LCA. CROI can facilitate LCA-based assessment of candidate CO2 capture, utilization, and storage technologies and offer a better measure of a technology's true potential to sequester CO2.[53]
- Sustainability Indexes - some indexes are a synthesis of surveys filled out by committees or auditors. These indexes, such as the S&P Dow Jones Sustainability Index, also include broad benchmark industry group weights. And as discussed in Section 2, a new Space Sustainability Rating (SSR) addresses the growing debris problem above the Karman line.

These frameworks or metrics align with specific transparency or information needs, and sometimes more than one solution is needed. However, the E-LCA approach has been gaining traction amongst those pursuing *comprehensive* understanding of environmental impacts.

Voluntary, Mandatory, and Government Buyer-Led Approaches

Looking across mature industries, most experience a period of development that led to environmental standardization and regulation. The aviation industry, for instance, underwent a significant degree of evolution over the past several decades. Today, regulatory frameworks exist at the airplane level for CO2 and noise, and at the engine level for nitrogen oxides (NOx), non-volatile particulate matter (nvPM) mass and particle number, carbon monoxide (CO), and unburned hydrocarbons (UHC). These standards ensure "that new technologies are incorporated into the aircraft fleet and that there is a level playing field internationally."[54]

As the space industry matures, evolving environmental standards can provide a meaningful framework to understand climate-related risks, future outlooks for climate goals, and key insights which could impact business models and financial health. To inform these climate-related risk forecasts, space sector stakeholders could work cooperatively across the industry value chain to establish environmental transparency and position the industry for longer-term sustainable growth. Looking forward, how can the space sector implement E-LCAs to strike the right balance between burden and benefit?

There are numerous challenges and opportunities when comparing voluntary to regulatory approaches for E-LCA implementation; neither approach is a perfect solution and both approaches have their drawbacks. The former invites deceptive practices or green-washing and the latter could discourage growth in the sector and may raise new issues when it comes to enforcement. Another option to consider would be to leverage the government's buying power to financially motivate sustainable behaviors.

Voluntary Disclosure Approach

Increasing public awareness of green products and services is already encouraging sustainability-related disclosures in many industries. A common finding across many studies of consumer ESG awareness is that consumers and business leaders increasingly support environmentally sustainable business practices. For instance, in IBM's Institute for Business Value 2021 survey of 16,000 global consumers in 10 major economies, 51 percent of respondents indicated that environmental sustainability had become more important to them today than it was 12 months ago. And 49 percent indicated that they paid a premium for products branded as either sustainable or socially responsible in the last 12 months. IBM's study also found that 39 percent of executives view environmental sustainability as a top priority, and more than half (53 percent) said it will be a top priority in three years.[55]

Voluntary ESG-related programs or climate-related financial disclosures can motivate consumers and investors, and they often require minimal oversight and review to implement. Unlike specific legislation overseen by regulatory authorities, voluntary practices are not subject to regulatory capture or to procedural obstruction by the targeted industry or polluter. However, voluntary disclosures often do not work well in practice due to the lack of accountability and opportunities for selective and misleading environmental disclosures, known as *greenwashing*. Greenwashing involves unsubstantiated claims to deceive investors or consumers into believing that a company's products or industrial processes are environmentally or socially friendly. Ian Christensen, director of private sector programs at Secure World Foundation, urges a more "holistic approach" that goes beyond the voluntary and warns that sole reliance on voluntary commitments will continue to "offer the potential for greenwashing."[56]

Another voluntary environmental disclosure challenge is the issue of *green-hushing*, the resistance of some commercial actors to publicly discuss their sustainability efforts. According to South Pole, a multinational climate consultancy, 23 percent of survey respondents from 12 globally representative regions, including the U.S., indicated that they have set science-based emission reduction targets but do not plan to publicize them. The survey found that green-hushing makes it difficult to hold companies accountable for specific goals and obstructs scrutiny of specific climate projects which might open up the door to criticism or even litigation. For instance, a company's climate mitigation strategy could be embarrassingly modest or controversial. Other companies may have robust environmental efforts but may keep them quiet to avoid drawing political scrutiny. Ultimately green-hushing is counterproductive to progress on environmental sustainability because it prevents knowledge sharing and best practices.[57]

Mandatory Requirements and Regulations Approach

On the other end of the spectrum from fully voluntary environmental disclosures, a mandatory approach could use laws, regulations, licenses, or other mechanisms to require space actors to share information on environmental impacts. Mandatory requirements can produce a level of consistent and comprehensive data that can encourage transparency and understanding and discourage green-washing tendencies, as well as give confidence to environmentally motivated investors. However, requirements and regulations addressing industrial development are often perceived as constraints on growth and innovation. Introducing a commitment to a planning system, such as E-LCAs, can support the space industry's expansion efforts and help avoid controversies and public backlash, but there is some risk that a new regulatory condition will be interpreted as a burden and affect return on investment. Mandating a specific form of disclosure could even slow progress toward improved tracking methodologies and more informative disclosures.

A recently proposed requirement from the Securities and Exchange Commission (SEC) might be applicable to encouraging life cycle assessments from the space industry. On March 21, 2022, the SEC proposed rule changes[****] that would require publicly traded companies to include climate-related disclosures in their registration statements and periodic reports.[58] These climate-related risks would include disclosure of a registrant's greenhouse gas (GHG) emissions from direct sources owned or controlled as well as indirect sources,[††††] thus creating a more transparent life cycle inventory. SEC Chair Gary Gensler noted that investors "recognize that climate risks can pose significant financial risks to companies, and investors need reliable information about climate risks to make informed investment decisions."[59] While these SEC requirements would only affect companies listed on U.S. stock exchanges, the rules would nudge many industries, including the space sector, towards greater familiarity with E-LCAs, as they require an inventory of direct and indirect GHG emissions. As of the early 2023, the SEC's "Climate Disclosure Rule" is still pending, with significant pushback on reporting indirect emissions from industry and some lawmakers in the House of Representatives. With concerns regarding future lawsuits, the SEC is now reconsidering the more

[****] The Enhancement and Standardization of Climate-Related Disclosures for Investors, https://www.sec.gov/rules/proposed/2022/33-11042.pdf.
[††††] Scope 1 – direct emissions released by company as a result of its own activities or industrial activity. Scope 2 – indirect emissions from the generation of purchased energy or a utility provider. Scope 3 - indirect emissions not included in Scope 2, could include other emissions due to a range of upstream activities in the supply chain.

demanding aspects of the proposed rule, the reporting of indirect carbon or Scope 3 emissions.[60]

Another challenge for implementing a mandatory life cycle assessment would be where to designate government authority oversight and implementation. There are no obvious subject matter experts retained in any one government agency because the space industry crosses several environmental and jurisdictional domains. And while the General Services Administration (GSA) currently provides some guidance on E-LCA methodology, they are not chartered or positioned to actively regulate and provide environmental oversight.

Even if regulatory agencies and Congress agreed on the need for new regulations, that would not necessarily resolve all limitations faced by voluntary approaches. Mandatory requirements and regulations require time to review and implement and, depending upon resources, they could be imperfectly enforced. In fact, the United Nations Environment Programme notes that despite the dramatic growth of environmental laws over the past three decades, there is a persistent lack of implementation and enforcement, falling short of what is needed to address global environmental threats.[61] The United States EPA, for instance, experienced a decline in enforcement resources from FYs 2006 through 2018, resulting in a reduction in compliance monitoring activities and concluded enforcement cases.[62]

Leveraging U.S. Government Scale and Procurement Power to Achieve Sustainability Goals

For this option, the U.S. government, including national security and civil satellite buyers, could incorporate acquisition standards that ask the space industry to provide environmental transparency across all stages of a satellite service or product life cycle.

The U.S. government is in a strong and influential position to effect long-term changes to the space industry as a large volume buyer and primary investor in many space systems. In the recent past, the U.S. government captured approximately 80 percent of U.S. satellite manufacturing revenues.[63] Therefore, the role of the U.S. government as an anchor tenant could help drive E-LCA implementation without relying on a blanket industry regulation.

The federal government is already applying its scale and procurement power to achieve sustainability goals. White House Executive Order (EO) 14057, issued in December 2021 and known as “The Federal Sustainability Plan,” sets out a range of ambitious goals to deliver an emissions reduction pathway to reduce U.S. greenhouse gas emissions by 50 to 52 percent from 2005 levels by 2030. The Plan calls for each agency to reduce waste and pollution and “promote a transition to a circular economy.”[64] In addition, the Inflation Reduction Act of 2022 includes several commitments to catalyze markets for a new clean energy economy, including funds for zero-emission U.S. Postal Service vehicles, support to develop and standardize environmental product declarations, and programs for low carbon labeling and procurement of clean, lower carbon construction materials.

In November 2022, several months after the SEC proposed regulations targeting greenhouse gas emissions, the DOD, General Services Administration (GSA), and NASA also proposed a new rule requiring federal suppliers to report direct (Scopes 1, 2) GHG emissions and “major contractors” who receive more than $50 million in federal contract obligations to report indirect (Scope 3) GHG emissions. The proposed regulation is intended to provide a better understanding of federal supply chain impacts.[65]

Even before these new procurement rules were proposed, U.S. government agencies had broad discretion to consider environmental and climate impacts in their procurement decisions; many government and defense organizations had already started to incorporate climate considerations across processes, plans, and decisions.[66]

Next Steps for Government Stakeholders: Institutionalize, Harmonize, and Research

National climate priorities, coupled with increasing efforts to steer the government buyer to more sustainable suppliers, provide a strong rationale for E-LCAs as a tool to measure greenhouse gas emissions and environmental footprints. This method for setting acquisition requirements could help establish commercial transparency, standardize metrics for measuring progress, and serve the U.S. leadership role in space. It also avoids the potential burden of negotiating and issuing requirements across the whole space industrial base and the potential misrepresentation and green-washing that can result from voluntary requirements.

Recommendations

U.S. government space missions and programs are motivated by public purpose and interests. Therefore, the U.S. government—as a large and influential buyer—may be able to catalyze a sustainable space industry—leading by example. Regardless of the path forward, either through government buyer acquisition requirements, mandatory regulation or voluntary incentives, the following recommendations can move the needle forward to enhance our understanding of space industry environmental impacts. These key steps can advance the space industry to a higher level of environmental sustainability and accountability through E-LCAs:

- ***Fund research for future environmental impact studies.*** It is important to document and fund key areas for further studies. There are several “unknown unknowns” that need to be addressed. Future studies should consider environmental impacts from rocket and reentry emissions in the upper atmosphere, specifically in the fragile stratospheric ozone, as well as terrestrial-based manufacturing impacts, spaceport land use, and local environmental impacts.

- ***Establish a center of excellence to ensure analytical rigor and objectivity.*** Ensuring E-LCA integrity and unbiased results will be key to overcoming vested interests among competing commercial companies vying for social and market benefits from lower environmental footprints. Objective parties, such as government or academic institutions, could provide the expertise and rigorous analysis needed across a range of satellite applications and products.

- ***Harmonize E-LCAs for an International User Base.*** The space industry is a network of international agencies and commercial companies operating in a multinational market. Closely coordinate with international allies including ESA, the United Kingdom, and Japan and eventually broaden the methodology to include, inspire, and lead spacefaring allies to harmonize E-LCA standards. Ultimately, the standardization journey must be open and inclusive to engender trust and agreement across the international space community.

Conclusion

Space industry advocates have long been leery of environmental scrutiny, often pointing to the degree to which space technology has contributed to human understanding of environmental problems. Indeed, compared to mature and global industries such as aviation, the space industry’s pollution volume, environmental impacts, and atmospheric emissions are most likely low. And while the space industry has taken numerous steps to mitigate environmental damage, such as a shift to greener fuels, the space sector's terrestrial impacts from expanding spaceport footprints and increased manufacturing and launch tempo are clearly on the upswing. Particle pollution contributions to the upper stratosphere could be harmful to the climate and ozone, causing pollution to upper atmospheric layers that are untouched by other industries.[67] The net collective impact of the space industry remains largely unknown at a time when the space industry is experiencing unprecedented growth.

A growing and secure space industrial base relies upon a foundational understanding of environmental effects across the entire life cycle, including terrestrial and atmospheric impacts. Government and commercial space stakeholders should not assume that life cycle study efforts are a burden and the unfortunate cost of doing business. Rather, circular economy principles and environmental life cycle assessments enable strategic insight across the value chain of space activities. Commercial space industry players could benefit by finding new opportunities for reusable or more efficient designs and by reducing costs and supply chain risks. Such efforts could also attract both domestic and international ESG-minded investors and customers to expand market access and increase profit.

As the impacts of climate change are increasingly felt around the world, the space sector will need to adapt. The U.S. space industry should not fall behind as other international space actors adopt sustainability measures such as E-LCAs. Instead, the U.S. government has an opportunity to act decisively and lead a thriving and circular space economy.

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