Environmental sustainability of future proposed space activities

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Abstract

As actors in the space sector are proposing ever more ambitious plans for the future, it is important to evaluate their consequences on the Earth's environment, which are yet poorly known. To address this gap, this study presents a streamlined Life Cycle Assessment of future space activities over the period from 2022 to 2050 based on plans that would likely drive the environmental impacts of the space sector if they were realised. Large constellations of satellites, space tourism, Moon missions, and space-based solar power were considered in a first scenario, while rocket-based point-to-point travel on Earth and Mars colonisation were also included in two other scenarios. To this aim, the model is based on data from companies' declarations and actual space systems and uses life cycle inventory and impact assessment data from the Strathclyde Space Systems Database. In the first scenario, the study finds that by 2050 proposed plans would lead to an unprecedented surge in the impacts of the space sector (x9 on climate change) and in the number of satellites in orbit (~112,000, all from large constellations). Ozone depletion from launch events could reach significant levels (6% of annual global impacts), while in a decade emissions of black carbon and aluminium oxide from rockets may alter the radiative balance of the atmosphere as much as present-day global aviation, although these effects are uncertain and poorly understood yet. Moreover, the mass injected into the atmosphere by re-entering artificial objects would become significant (~27x the natural level for aluminium), while its environmental consequences remain largely unquantified. In the two other scenarios, results indicate that speculative plans of rocket-based point-to-point travel on Earth and Mars colonisation could deplete ozone several times as much as all other human activities combined, while air acidification and climate change could reach several percent of annual global impacts and planetary boundaries. The mitigation of these impacts using low carbon fuels would be limited by supply availability and by the emission of non-CO2 climate forcers and ozone-destroying compounds during launch and re-entry. Consequently, environmental sustainability is identified as a potential limiting factor to the development of intense space activities and to making humanity a multi-planetary species. Furthermore, political and social acceptability could play a major role in the development of recreational space travel since it exacerbates environmental inequalities due to an unparalleled combination of economic inaccessibility and high environmental footprints per passenger. Overall, results strongly suggest that there is a pressing need to include environmental considerations in addition to technical and economic analyses in space projects definition and space systems design.

Keywords: Life Cycle Assessment, Environmental impact, Space sustainability, Space system, Future, Scenario

Acronyms & Abbreviations

AA	Air Acidification
AGI	Annual Global Impact
Al	Aluminium
AO	Aluminium Oxide (Al2O3)
AP	Ammonium Perchlorate
BC	Black Carbon
CC	Climate Change
CEA	Chemical Equilibrium with Applications
CF	Characterisation Factor
CtP	Cargo-to-Person
DAC	Direct Air Capture
EtE	Earth-to-Earth
EU	European Union
FI	Flow Indicator
HTPB	Hydroxyl-terminated Polybutadiene
IEA	International Energy Agency
JRC	Joint Research Center
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LHA	Long-haul Aviation
LM	Long March
LOX	Liquid Oxygen
OD	Ozone Depletion
PB	Planetary Boundary
PM	Particulate Matter
PMD	Post Mission Disposal
PO	Photochemical Oxidation
RD	Resource Depletion
RP-1	Rocket Propellant 1 (kerosene)

SBSP	Space-based Solar Power
SLS	Space Launch System
SS304L	Stainless Steel 304L
SSA	Supersonic Aviation
SSSD	Strathclyde Space Systems Database
UBS	Union Bank of Switzerland
UDMH	Unsymmetrical Dimethylhydrazine
UHNWI	Ultra-high Net Worth Individuals
US	United States

1. Introduction

The space sector is undergoing a period of fast expansion and change driven by a set of technological and business model innovations, which leads to a significant decrease in satellite and launch vehicle financial costs. This enables new markets and services for space activities, making more ambitious projects feasible. As a result, in the past few years some space actors, most often private, have proposed projects and set objectives that would lead to an unprecedented surge in launch rates and in the number of objects in orbit, thereby profoundly transforming space operations [1]. This includes the deployment of multiple large constellations consisting of thousands to tens of thousands of satellites, the expansion of suborbital and orbital tourism, the new race to the Moon, the development of space-based solar power, but also much more speculative plans such as rocket-based transportation solutions for point-to-point travel on Earth and the establishment of a self-sustaining colony on Mars [2]. However, these plans could threaten the sustainability of space activities by increasing the stress on the orbital environment, resulting in the proliferation of space debris, but also by increasing the stress of the global space sector on the Earth’s resources and ecosystems. As the world is becoming more aware of the urgent need to reduce the environmental footprint of human activities, while at the same time becoming increasingly reliant on space-based assets for various essential services (e.g. communications, navigation, climate and environmental monitoring, emergency response and disaster relief), ensuring a sustainable future for space activities is critical.

While the space debris issue has received large scientific interest and is well understood, due to its unique nature, the space sector has historically been exempted from many of the leading legislative and regulatory instruments on environmental protection. However, this left the industry unable to account for its environmental impacts, despite growing pressure on the need to scientifically quantify the environmental consequences of its operations. For this reason, the European Space Agency (ESA) first began exploring the environmental impacts of its projects in 2009, having identified Life Cycle Assessment (LCA) as being the most appropriate methodology for this purpose [3]. LCA is a standardised methodology for scientifically quantifying environmental impacts of products, processes and services [4]. Since then, numerous LCA studies have been completed in the space sector that have provided valuable insights [5]. In particular, a quantitative assessment of the sustainability of the global space sector was carried out by Wilson et al. [6], [7]. Environmental, social, and economic impacts were evaluated using streamlined Life Cycle Sustainability Assessment (LCSA) for 2018 and in a future scenario of the space sector assuming 750 launches per year delivering 5000 spacecraft into orbit. This assessment provided a first-order estimation of the sustainability of the space sector across various indicators and in a credible medium-term scenario based on the space industry's trends. In addition to LCA studies, some authors have investigated more specifically the effects of launchers' emissions on climate change and stratospheric ozone depletion under past or hypothetical launch rates for the global space sector (e.g. [8], [9]), or focusing on a specific space activity (e.g. Ross et al. on space tourism [10], [11], Larson et al. on space-based solar power [12]). However, in the context of a rapid change of scale, despite these various sustainability studies the evolution of the environmental impacts of the global space sector remains poorly known, although they could constitute a fundamental limit to its development as suggested by Miraux [13].

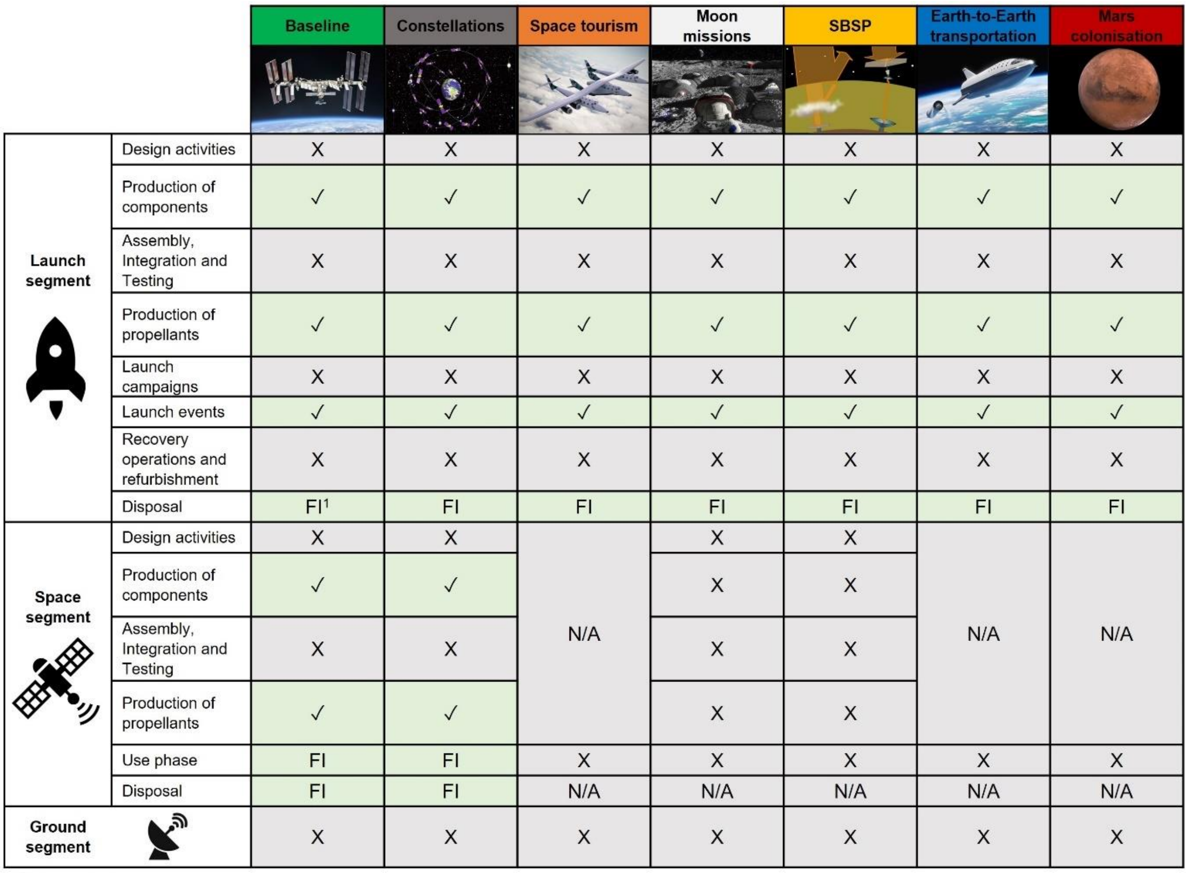
Therefore, there is an urgent need for a quantitative assessment of the environmental impacts of plans actually proposed by space actors to highlight the future associated challenges. It is the first step to allowing them to mitigate these impacts and adapt their objectives in accordance with sustainability constraints. For this reason, this paper describes different scenarios of the evolution of space activities, which were constructed based on real proposals from major actors of the space sector for the period from 2022 to 2050. For each scenario, the paper presents the results of a streamlined LCA that was conducted to evaluate the environmental impacts of these plans using simplified models of actual space systems. Then, the implications of these results on future space systems design are explored along with some mitigation options, while the potential evolution of social and regulatory pressures on the space sector is discussed.

2. Methodology

2.1. Goal and scope

The objective of the study is to estimate the environmental impacts of proposed space activities over the period 2022 to 2050. To this aim, a review of proposed plans has been carried out to identify activities to include within the scope. They have been selected based on their potential to become the major drivers of future launch activity and space traffic: large constellations, space tourism, Moon missions, space-based solar power (SBSP) Earth-to-Earth (EtE) transportation, and Mars colonisation. Baseline activities, i.e. 2021 space activities excluding those just listed, were also analysed for comparison. The year 2050 was chosen as the end of the investigated period because it coincides with milestones of some proposed plans (like Mars colonisation and SBSP, as discussed in Section 2.3) while being a key year for global sustainability targets (global CO2 emissions need to reach net zero by 2050 to limit global warming to 1.5°C as called for in the Paris Agreement). Proposals, launchers, and satellites modelled in the study are based on real company declarations, roadmaps, market forecasts and actual space systems. However, we emphasise that this study does not attempt to predict future impacts, nor intends to shed light on those of any particular company or institution, but rather aims at assessing the approximate scale of the environmental impacts that would be caused if announced plans were implemented. In addition, proposed plans will be considered as such, without regard for their technical or economic feasibility. The stated values refer to current operating conditions over the investigated period.

Since this study is investigating future space activities – in some cases highly speculative ones – operated by different organisations across the world and using a large variety of systems and technologies, lifecycle phases included in the scope of the LCA needed to have as little dependency as possible with respect to these factors to reduce uncertainty. At the same time, the scope needed to capture the core of space activities and their specificities. The balance between these two constraints led to a first definition of the scope, which was then significantly influenced by a lack of data availability. As such, for each activity considered, the scope of the LCA related to the launch segment includes the production of launchers' components, the production of propellants, and the combustion of propellants during launch events. In terms of the space segment, the production of satellites' components and propellants of baseline and constellation activities is included. For other activities that are entirely based on launch systems (space tourism, EtE, Mars colonisation), the production of components and propellants of the payload is not applicable, except for capsules, which are included in the launch segment. The production of materials in the payload of lunar missions, of SBSP activities and of cargo ships sent to Mars is not included due to lack of data availability and high modelling complexity. These lifecycle phases were selected because the productions of launcher and satellite components and propellants were found to be hotspots for air acidification and climate change by Wilson et al. [7]. In addition, the launch event has been consistently identified as the major contributor to ozone depletion by far in previous studies, and to be also relevant for several other impact categories including climate change [5], [7]. Then, for the use and disposal phases, some flow indicators (FIs) such as the number of objects or mass in orbit and the re-entry mass influx are considered (Fig.1).



		Baseline	Constellations	Space tourism	Moon missions	SBSP	Earth-to-Earth transportation	Mars colonisation
Launch segment	Design activities	X	X	X	X	X	X	X
	Production of components	✓	✓	✓	✓	✓	✓	✓
	Assembly, Integration and Testing	X	X	X	X	X	X	X
	Production of propellants	✓	✓	✓	✓	✓	✓	✓
	Launch campaigns	X	X	X	X	X	X	X
	Launch events	✓	✓	✓	✓	✓	✓	✓
	Recovery operations and refurbishment	X	X	X	X	X	X	X
	Disposal	FI[1]	FI	FI	FI	FI	FI	FI
Space segment	Design activities	X	X	N/A	X	X	N/A	N/A
	Production of components	✓	✓		X	X		
	Assembly, Integration and Testing	X	X		X	X		
	Production of propellants	✓	✓		X	X		
	Use phase	FI	FI	X	X	X	X	X
	Disposal	FI	FI	N/A	N/A	N/A	N/A	N/A
Ground segment		X	X	X	X	X	X	X

[1] Flow indicator

Figure 1. Scope of the LCA.

The impact categories considered in this study are reported in Table 1. However, due to current knowledge gaps and high complexity in the estimation of impacts related to lifecycle phases that are specific to space activities (launch, orbit and re-entry), these impacts are not fully characterised into impact categories. Nevertheless, to provide as much insight as possible, flows of relevant physical quantities were reported when sufficient data was available. This will allow subsequent studies to build on the results of this paper once impact characterisation will be possible. Table 2 expands on how the different aspects of each phase were treated. For the launch and re-entry phases, a full characterisation would have modified the LCIA results associated with impact categories listed in Table 1. For this reason, the implications for the limitations of the study are discussed in more detail in Section 2.4. The potential severity of each phenomenon is also estimated based on past studies to help the reader better understand the stakes. Furthermore, in terms of the orbit phase, the consequences of proposed plans on space debris and ground-based astronomy will only be discussed qualitatively based on the calculated FIs, since translating these quantities into additional relevant impact categories would require thorough, dedicated analyses beyond the capabilities of this study.

Table 1. Environmental impact categories investigated in this study.

Impact category	Abbreviation	LCIA method
Air acidification	AA	CML
Climate change	CC	IPCC
Ozone Depletion	OD	CML
Particulate Matter	PM	ReCiPe
Photochemical Oxidation	PO	ReCiPe
Resource Depletion	RD	CML

Table 2. Detail of environmental impact categories investigated in this study for space-specific lifecycle phases.

Phase	Relevant impact category	Relevant physical quantity / phenomenon	Potential severity	Characterisation in this study
Launch	AA, CC, OD, PM, PO	N2, CO2, CO, H2 emissions	Low [7], [8]	Ground-based
		H2O emissions	Moderate [8], [14], [15]	CC: aviation-based
		NOx emissions	Moderate [14] High (OD) [9]	AA, PM, PO: ground-based CC: aviation-based OD: stratosphere-based estimate
		ClOx, HOx, HCl emissions	High [9]	OD: stratosphere-based estimate
		Al2O3 emissions	High [8]	FI
		Black carbon emissions	High [8]	CC: aviation-based (sensitivity)
Orbit	Space debris, interference with astronomy	Number of satellites in orbit	High [16], [17]	FI
		Number of operational satellites in orbit		FI
Re-entry	AA, CC, OD, PM, PO	Mass of rocket bodies re-entering	Unknown	FI

		Mass of satellites re-entering		FI
		Mass of aluminium (and Al_2O_3) emitted upon re-entry		FI
		NOx produced in shock waves	Moderate [14], [18], [19]	Same as launch (sensitivity)

2.2. Data sources and hypotheses

The main source of data for this study is the Strathclyde Space Systems Database (SSSD), which was developed at the University of Strathclyde and is the first Life Cycle Sustainability Assessment tool for space systems [6]. Regarding the launch segment, the SSSD provided ready-to-use Life Cycle Impact Assessment (LCIA) results for the scope considered for several launchers involved in space activities modelled: Atlas V, Falcon 9, Falcon Heavy, Soyuz 2.1 and Long March 3B/E. Note that the reusability of the first stages of Falcon 9 was factored in assuming an average of 20 uses before disposal. This rough estimate is based on SpaceX's claims that the last iteration of its rocket is currently capable of 10 flights without major refurbishment [20], and seems reachable within the decade.

However, several additional launchers not included in the SSSD had to be modelled because they are used in the proposed plans. These include variations of launchers of the Long March family, Starship Super Heavy, New Glenn, Vulcan Centaur 6, Ariane 64, SpaceShipTwo, and New Shepard. The production and manufacturing of the components of these additional launchers were approximated by using LCIA results of a generic launcher model as available in the SSSD. In the activities described most launches are made using semi or fully reusable launchers planned to operate with high reuse rates, meaning that the environmental burdens associated with the production and manufacturing of components are significantly reduced across all impact categories, thereby reducing the importance of this step in total impacts. In this regard, stages reuse rates have been based on announced objectives or using assumptions based on the level of heritage in reusability of each launch system operator. Table 3 outlines the various hypotheses made for the modelling of relevant launch systems.

In terms of the production of propellants, the masses of loaded propellants were collected for each launcher from online sources (Tab.3), and impact assessment results were readily obtained from per kg LCIA results available in the SSSD. To estimate the impacts of launch events, the mass fractions of exhaust compounds were provided in the SSSD for the different propellant combinations involved. These emissions then need to be converted into impact categories using characterisation factors (CFs). However, currently available CFs are not altitude dependent, meaning that launchers' exhaust components have the same effect regardless of their altitude of emission. Yet, as launchers emit across all the layers of the atmosphere during their ascent, injecting material directly into regions of concern such as the stratosphere and the ozone layer, a large deviation from conventional ground-based CFs can be expected [8], [9]. Therefore, CFs of exhaust gas species available in the SSSD (and reported in [6]) are no exception, except for ClOx, HOx, NOx, and HCl factors for ozone depletion from [9] that include altitude effects, but are uncertain. To improve this, CFs provided by Lee et al. to estimate the impacts of aircraft H_2O and NOx emissions on climate change were added [14]. However, these CFs are likely to be not representative of the actual effects at higher altitudes, like for H_2O, whose climate impacts were found to substantially increase at stratospheric altitudes [15]. Then, the effect of particles (aluminium oxide Al_2O_3, black carbon) was initially not accounted for in the SSSD due to knowledge gaps in the literature despite being a major source of concern. Available climate change CF for black carbon (BC) varies from 460 kgCO2eq / kg (Intergovernmental Panel on Climate Change [21], ground-based) to 1166 kgCO2eq / kg (Lee et al. [14], aviation-based), while for other relevant impact categories like ozone depletion, CFs are not available. For Al2O3, no CFs were found. However, Ross et al. warned that the accumulation of Al2O3 and BC emitted by rockets in the stratosphere could significantly increase the impacts of launch emissions on climate change (up to several orders of magnitude) and on ozone depletion by altering its radiative balance and triggering ozone-destroying reactions [8], [22]. Unfortunately, these complex effects are yet poorly understood and cannot be translated into a ready-to-use CF. Consequently, both Al2O3 and BC will be reported as FIs and not included in the impacts, with the most relevant emissions indices of the SSSD being: 330g Al2O3/kg of propellant for aluminium-based solid boosters, 20g BC/kg of propellant for kerosene-fuelled rockets, and 0.8g BC/kg of propellant for methane-fuelled rockets (e.g. 25x less than kerosene). However, a sensitivity analysis will be performed on the final results on climate change using the aviation-based CF for BC. Flows included and characterised for launch events are outlined in Table 2. Note that the total amount of propellant produced and burnt was assumed to be equal to the amount of propellant loaded in the launchers for launch events, meaning that the propellant consumed during tests or lost during fuelling operations was not accounted for.

The impacts of the re-entry of orbital launchers have also been investigated but not included in the final results due to high uncertainty. Park and Rakich [18] estimated that at each re-entry of the Space Shuttle, a mass of NOx equivalent to 17.5%±5.3% of the mass of the vehicle was produced in the shock wave formed around it, although this might vary considerably depending on the vehicle's aero-thermodynamic properties and re-entry profile. Because of the lack of accurate data on those properties, it was assumed that reusable and expendable upper stages would produce similar amounts of NOx. For lower stages, it was assumed that little to no NOx would be generated as they do not reach these high hypersonic velocities at lower atmospheric regions where real gas effects become important. The climate CF for NOx was also based on aircraft factors, although re-entry NOx would be mainly emitted at much higher altitudes. Like BC, the associated impacts will be discussed separately from other lifecycle impacts in a sensitivity analysis as a consequence of these assumptions.

In terms of the space segment, which is only relevant in baseline and constellation activities (otherwise excluded or not applicable), a simple approach was used. A typical constellation satellite was constructed based on available data from manufacturers combined with estimations of component mass breakdowns. The main functional parts and elements of a satellite have been included in the modelling. Table 4 outlines the resulting mass distribution of the satellite. Then, impact assessment results per kg of component or propellant from the SSSD are used to evaluate the total impacts associated with the production. Satellites from different constellations are then scaled proportionately to their mass with respect to this reference model. Although satellites of baseline activities are likely to differ widely from this reference, the same approach was also used for simplicity.

Then, LCIA results are compared to annual global impacts (AGIs), which refer to the sum of the impacts of all anthropogenic activities over a year, and to planetary boundaries (PBs), which describe ecological limits within which humanity can safely operate. To this aim, normalisation factors provided by the European Commission's Joint Research Center (JRC) are used [23], [24]. Note that these AGIs are based on the most recent data, which are for the year 2010.

Table 3. Modelling parameters of launchers not readily available in the SSSD.

	Dry mass[2] (t)	Utilisation regime	Propellant mass (t)	O/F ratio	Propellants	Capacity	Sources
Starship Super Heavy	395	Fully reusable	4600	3.6	Methalox	100t 1000 passengers (EtE) 10 passengers (Moon tourism)	[25], [26]
Booster Super Heavy	275	30x (low) 1000x (high)	3400				
Starship	120	30x (low) 100x (high)	1200				
Mars vehicle	395	Fully reusable	4600	3.6	Methalox	100t 100 passengers	[25]–[27]
Booster Super Heavy	275	1000x	3400				
Interplanetary spaceship	120	12x	1200				
Tanker	120	100x	1200 (+240)				
Long March 5	84	Expendable	768			25t	[28]
Boosters	55		571	2.6	Kerolox		
Stage 1	22		165	5.5	Hydrolox		
Stage 2	7		32	6.0	Hydrolox		
Long March 9	434	Semi-reusable	4000			140t	[29], estimations
Boosters	287	1x	2973	2.6	Kerolox		
Stage 1	112	20x	860	5.5	Hydrolox		
Stage 2	35	1x	167	6.0	Hydrolox		
New Glenn	126	Semi-reusable	1108			45t	[30]
Stage 1	110	20x	1000	3.8	Kerolox		
Stage 2	16	1x	108	6.0	Hydrolox		
Vulcan Centaur 6	43	Expendable	546			27t	[31]–[33] estimations
Boosters	25		320	69% AP, 19% Al, 12% HTPB	AP, Al /HTPB		
Stage 1	13		172	3.8	Methalox		
Stage 2	6		54	5.9	Hydrolox		
Ariane 64	65	Expendable	745			22t	[34], [35], estimations
Boosters	44		574	69% AP, 19% Al, 12% HTPB	AP, Al /HTPB		
Stage 1	12		140	5.3	Hydrolox		
Stage 2	9		31	6.1	Hydrolox		

Space Launch System		Expendable				95-130t	[36]
Block 1	192		2268				
Block 1B/2	203		2368				
Boosters	104		1251	69% AP, 19% Al, 12% HTPB	AP, Al /HTPB		
Stage 1	85		988	6.0	Hydrolox		
Stage 2							
Block 1	3		29	5.9	Hydrolox		
Block 1B/2	14		129				
SpaceShipTwo		Fully reusable				6 passengers	[37], estimations
Aircraft carrier	-	Infinite	16	N/A	Kerosene		
Ship	3	20x	7	6.0	NO2/HTPB		
New Shepard	35	Fully reusable 20x	22	6.0	Hydrolox	6 passengers	[11], estimations

[2] metric tons

Table 4. Modelling parameters of satellites.

Part	Mass distribution
Solar panels	29%
Batteries	9%
Power Processing Unit	8%
Hall Effect Thruster	3%
Propellant	13%
High pressure vessel	12%
Miscellaneous (structures as proxy: 90% AA6061 ; 10% AA7075)	27%

2.3. Modelling of activities

2.3.1. Baseline activities

Baseline activities have been based on the year 2021. The 2021 space launch record was collected from an online database [38]. With the launchers already modelled in the SSSD, 74 out of 133 launches can be represented. Most of the missing launches (29) are serviced by launchers of the Long March (LM) family. LCIA results of missing versions of LM launchers are obtained by applying a scaling factor (ratio of lift-off masses) either based on the known LCIA results of LM 3B (available in the SSSD) or of LM 5 (modelled according to the approach described in Section 2.2), depending on propellant combinations. This allows extending the coverage to 112 out of 133 launches. As most of the remainder is composed of small launchers, this is a good representation of 2021 activities in terms of the total mass of payload sent to orbit. However, Starlink and OneWeb launches need to be withdrawn from these 2021 activities because they do not apply as baseline activities. They will be described subsequently in constellation activities. Then, since satellites in baseline activities are typically produced in very low volumes, an average number of 5 spacecraft models is assumed to be created per mission with a 1:1 mass ratio with respect to the final model [6]. Other data related to space traffic and re-entry mass influx were collected [39], [40]. Baseline activities are assumed to remain constant up to 2050. It should be noted that this is likely an underestimation, since if the other hypothetical modelled markets emerge, launch costs might be reduced considerably, shifting the market equilibrium towards more baseline activities.

2.3.2. Large constellations

In 2020, Curzi et al. [41] found about one hundred companies or agencies proposing constellations. As highlighted by Pardini and Anselmo [42], because these propositions are evolving rapidly and their market potential and economic profitability are uncertain, it is difficult to provide an up-to-date overview of all of them. In this study, most of the data on constellations was collected from the website NewSpace Index [43], with updates and complements from a variety of online sources (Tab.5). In particular, the number of satellites per constellation and their unitary masses were gathered. When the unitary masses were not provided by the manufacturer, they were assumed equivalent to those of comparable constellations. This allowed ranking constellation plans according to their mass in their fully deployed configuration – which is a good indicator of their ranking in terms of environmental impacts – and to focus on a few of them by applying a cut-off rule. As such, considering only the ten heaviest constellations, more than 99% of the total mass of all planned constellations can be described. Then, contrarily to satellites of baseline activities, constellation satellites are typically mass-produced meaning that it can be assumed that no other spacecraft are built than those sent into orbit.

Constellation activities have, therefore, been narrowed down to only 10 different proposals. While the business viability of these 10 coexisting constellations is not guaranteed, it is interesting to evaluate the impacts of their full implementation. Together, they represent a total of about 92,000 satellites in their fully deployed configurations, about 40,000 metric tons (t). For each of these proposals, other relevant data were collected based on company declarations or reasonable assumptions (Tab.5). Satellites are assumed to be launched at a constant rate over their deployment period until the target population is reached, plus additional launches associated with the replenishment of satellites that have reached their end-of-life. According to operators' declarations, after their end-of-life most satellites are expected to re-enter the Earth's atmosphere within a year or so thanks to passive orbital decay at low altitudes, while in most cases satellites at higher altitudes will either make a deorbit manoeuvre or be removed by a servicer spacecraft within 10 years. In this study, all satellites of a given constellation are assumed to re-enter the Earth's atmosphere within the same Post Mission Disposal (PMD) time. In addition, a 0% failure rate is assumed for simplicity, which is consistent since such a high number of satellites sent to orbit would necessarily have to be operated with very high reliability standards to be sustainable [42], [44], [45]. Note that these assumptions would constitute behaviours of satellite operators much more virtuous than that recommended by space debris mitigation guidelines (max. 25-year PMD time, min. 90% PMD success rate [46]). Launchers are assumed to operate at their full payload capacity. The re-entry mass influx is also calculated using satellites, launchers core and upper stages dry masses. The mass of servicer spacecraft for orbit removal is neglected. Then, the mass of material emitted in the atmosphere is obtained using average survivability rates assumed by

Schulz and Glassmeier [40], i.e. 35% for upper stages, 70% for core stages and 0% for constellations satellites. Only aluminium emission is investigated here to provide an indication, assuming 40% mass composition in satellites and 80% in rocket bodies, again using assumptions from the same study. Note that for semi-reusable launchers only the expendable upper stage mass is accounted for, while a 100% survivability rate is assumed for the reusable upper stages of fully reusable launchers, meaning that mass from thermal ablation is neglected.

Table 5. Large constellations modelling parameters. Assumed values are written in italic.

Company	N° sats	N° sats already in orbit	Starting date	Full deployment date	Launcher	Launcher capacity (t)	Average satellite mass (kg)	Satellite propellant	Lifetime (y)	PMD time (y)	Sources
SpaceX Starlink Gen2	30 000	0	2022	2040	Starship Super Heavy	100	850	Krypton	*5*	*1*	[47]–[50]
SpaceX Starlink Gen1	10220	1780	2021	2030	Falcon 9 (2022 only) Starship Super Heavy	100	260	Krypton	5	1	[47], [50]–[52]
China SatNet (Guo Wang)	12 992	0	*2024*	*2034*	*Long March 5*	25	*260*	*Xenon*	*7*	*2*	[53]
Telesat Lightspeed	1371	2	2023	*2033*	New Glenn	45	700	Krypton	10	2	[54]–[56]
OneWeb	6154	218	2021	*2030*	Falcon 9	8	150	Xenon	6	1	[57]–[60]
Boeing	5789	0	*2026*	2038	*Atlas V*	10	*125*	*Xenon*	*7*	*2*	[56]
Astra	13620	0	2022	*2032*	*Falcon 9*	23	*50*	*Xenon*	*7*	*2*	[61]
Mangata networks	791	0	2024	*2034*	*Falcon 9*	23	500	*Xenon*	*7*	*2*	[62]
Amazon Kuiper	7774	0	2022	2029 (3246 sats) 2032 (7774 sats)	Atlas V (6%)[3] Vulcan Centaur 6 (19%) Ariane 64 (13%) New Glenn (61%)	10 27 22 45	700	*Xenon*	*7*	*2*	[56], [63]–[65]
GalaxySpace	999	1	2022	*2032*	Long March 2C	4	190	*Xenon*	*7*	*2*	[66], [67]

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[3] Percentage of total launches based on recent announcements [65], assuming new contracts for each launch operator for the replenishment of launched satellites, and subsequent completion of deployment entirely with New Glenn.

2.3.3. Moon missions

In recent years, national space agencies have revealed several plans for lunar exploration for the next decades. The Artemis program is the National Aeronautics and Space Administration's (NASA) program to return humans to the Moon by 2025, and to ensure a sustainable presence to prepare for missions to Mars. The first mission, Artemis 1, is an uncrewed lunar orbit and return launched by the Space Launch System (SLS) Block 1, which is planned for 2022. Then, one mission is planned every year from 2024 to 2033 using different versions of the SLS (Block 1, 1B and 2) [68]. Moreover, international and commercial partners of NASA will support the Artemis program with robotic missions in the context of the Commercial Lunar Payload Services program (1 launch of Vulcan Centaur 6, 4 of Falcon 9, and 1 of Falcon Heavy, between 2022 and 2024) and Lunar Gateway program (1 Falcon Heavy in 2024). The transport of astronauts from the Lunar Gateway to the surface of the Moon and back will be provided by the Starship Human Landing System, which was assumed to require 1 launch of the Starship Super Heavy plus 9 launches of its tanker version for refuelling in Earth's orbit (a range between 4 and 14 launches was reported) [69]. This system will be tested in 2023 before its use in 2025.

In addition, the International Lunar Research Station will be developed by the China National Space Administration and Roscosmos. It consists of a space station in the Moon's orbit, a base on its surface and a set of robots for exploration and in-site utilisation of resources [70]. The reconnaissance phase, which is the first of this plan, is expected to be completed in 2025 (3 launches of Soyuz 2 for Luna 25-27, and 2 of LM 5 for Chang'e 6 and 7 are pending). A construction phase will follow between 2026 and 2035 (1 LM 5 for Chang'e 8, 1 Angara A5 for Luna 28, and 1 LM 9 or Yenisei every year between 2032 and 2035 for IRLS 1-5). Launches of Angara A5 and Yenisei have been modelled as launches of LM 5 and LM 9, respectively. Then, the utilisation phase is expected to begin in 2036, but no launches are planned yet.

These projects will be accompanied by several other missions from various organisations that are currently scheduled from 2022 to 2027. Nine missions have been modelled, with 6 launches of Falcon 9, 2 Ariane 64 and 1 New Glenn. After 2035, no launches are scheduled yet. However, since these activities would have paved the way for more intense and frequent Moon missions by that time, it was assumed that average activities from 2022 to 2035 (>4 launches/year on average) would be doubled between 2035 and 2050.

2.3.4. Space-based solar power

The concept of harvesting the energy of the sun with large solar panels in orbit and using wireless transmission to receivers on the ground has been widely discussed for decades. However, progress in efficiencies and reduction of costs of launches makes the realisation of the first space-based solar power (SBSP) plants realistic within the next decades. In addition, SBSP is receiving growing attention in the context of the energy transition with the hope to use it as a lever to decarbonise global energy production. Illustrating, China has announced plans to build and operate a megawatt-level plant by 2030, with the objective to reach a commercial gigawatt-level plant by 2050. In terms of launch requirements, it is expected to necessitate more than 100 launches of LM 9 [71]. Similarly, the United Kingdom has developed the Space Energy Initiative to help deliver its net zero pledge, with the aim to launch 25 systems generating 2GW each, along with some prototypes [72]. The entire project is expected to require 569 launches using 60 Starship Super Heavy. A detailed LCA study has been carried out and found an average carbon intensity of energy production of

23.6gCO2/kWh [72]. Here, to remain consistent with the methodology of the present study and for simplicity, impacts will just be roughly estimated and only for the launch segment, assuming that these launches are distributed uniformly from 2026 to 2050.

2.3.5. Space tourism

Space tourism is the market of travel to space for recreational purposes, including short duration suborbital flights and longer duration orbital trips into space in capsules or space hotels, or trips beyond Earth's orbit.

Regarding suborbital space tourism, Virgin Galactic and Blue Origin are assumed to dominate the market in terms of the number of seats sold due to their successful first commercial flights in July 2021. Virgin Galactic reported having sold 700 seats in 2021 representing ~117 launches at full passenger capacity, while the next launches are planned only by late 2022 [73]. In addition, they reported that about 60,000 people had approached the company and stated their interest in flying with them [73]. Furthermore, they announced that their objective was to launch at a rate of 400 flights per year per spaceport [74]. On the other hand, Blue Origin has not declared launch rate targets. However, in an auction the company ran in 2021, there were 7,600 registered bidders [75]. In order to avoid making predictions on which of the two companies will dominate the market, they were assumed to sell the same number of seats every year. Since little information is available about the long-term plans, two scenarios were built based on basic assumptions. In the first scenario consistent with a low growth of space tourism activities, Virgin Galactic (and Blue Origin) fulfils its plan to launch at a rate of 400 flights per year with its first spaceport by 2030. Then, for each company, an additional spaceport is built and reaches this level of activity every 10 years, leading to 3 fully operating spaceports per company by 2050. In this scenario, all the bidders of the 2021 Blue Origin auction would have flown with the company by 2029, while Virgin Galactic would cross the 60,000 passenger threshold by 2042. By 2028, about 2,200 flights would have been undertaken, which is more conservative than a reference market forecast [76]. In the second scenario, consistent with high growth of space tourism activities, 10 fully operating spaceports per company are assumed to be reached by 2050.

In terms of orbital tourism, Merrill Lynch reported strong interest from the public in space travel, with 50% of the population surveyed willing to pay 50,000$ (US) for an orbital trip [77]. Based on past or incoming missions, Falcon 9 and Starship Super Heavy vehicles are likely to be major vehicles used for future orbital and tourism missions, and even for Moon or interplanetary tourism missions as regards Starship Super Heavy. As such, announced plans for 2022 and 2023 involving these vehicles have been modelled. However, since too little information was available for subsequent years, by 2030 launch rates are simply assumed to reach 10 launches/year/vehicle in the low growth scenario and 100 in the high growth scenario. Then, since these activities will likely be disrupted by the advent of Earth-to-Earth transportation and Mars colonisation activities, and to avoid making ungrounded assumptions regarding their evolution, these launch rates are assumed to remain constant over the 2030-2050 period.

2.3.6. Earth-to-Earth transportation

Earth-to-Earth (EtE) transportation is a category of suborbital spaceflight in which a spacecraft transports passengers or cargo between two locations on Earth at a very high speed. SpaceX has revealed plans to use its Starship Super Heavy for this purpose, advertising "most international long distance trips completed in 30 minutes or less" for 8 destinations on its website [78].

To evaluate a potential launch traffic for passenger EtE transportation (cargo transportation is not considered), several approaches are proposed. A first approach consists in assuming that it will replace a certain market share of supersonic commercial air travel, which is assumed to start again from 2030 as announced by some companies. Weit et al. [79] proposed a supersonic commercial flight high demand scenario with 786 flights/day in 2035 and 1180 flights/day in 2050, with 55 passengers/flight. If a 25% market share taken by rocket EtE transportation is assumed, this leads to about 11 flights/day (~4,000 flights/year) by 2035 assuming that each flight takes 1,000 passengers as announced (although likely overestimated) [80]. This is slightly less than the flight rate necessary to allow 4 destinations to have one back-and-forth connection with each other every day. However, to compete economically with supersonic airliners, reusable launchers used for EtE transportation will need to be operated with high daily launch rates to reduce costs per flight. As such, assuming a smaller launch rate would probably make EtE uncompetitive. In addition, by 2050 about 5,900 flights per year would be performed, which would not be enough to add a fifth destination with a back-and-forth connection. This is, therefore, a conservative scenario. A 100% market share has also been investigated, leading to ~24,000 flights/year by 2050 enabling daily back-and-forth connections between 8 destinations. The two resulting scenarios of this approach based on the supersonic aviation market will later be referred as SSA-25 and SSA-100 for 25% and 100% market shares, respectively.

A second approach consists in assuming that EtE will replace a certain market share of airline flights longer than 10 hours. With this approach, UBS (Union Bank of Switzerland) estimated in a forecast that in a decade rocket EtE transportation would service 5% of the 150 million seats/year [81]. With 1,000 seats/flight, this would mean about 7,500 rocket EtE flights/year by 2032, a development occurring much faster and earlier than with the first approach. Since the evolution of EtE beyond this date was not forecasted by UBS, the evolution of the number of flights in subsequent years had to be assumed. Such a success of EtE transportation only within a few years of its first commercial flight would likely lead to a larger switching rate of passengers of airline flights longer than 10 hours to EtE that we assume will reach 25% by 2050. Note that the 2050 seats demand is assumed to be the same as that reported by UBS for 2030. This leads to ~38,000 flights/year by 2050, enabling daily back-and-forth connections between 10 destinations. This scenario will be later referred as LHA (long-haul aviation).

This way, three scenarios of the development of EtE transportation will be investigated. All flights were assumed to be done with the Starship Super Heavy, with a number of uses before disposal of 100 per Starship and 1,000 per Super Heavy booster. As it will be verified, assuming a higher number of uses has a negligible effect on LCIA results, though as noted earlier, it might lead to lower launch costs and ticket prices, leading to an EtE market equilibrium with higher launch rates. Nevertheless, this indirect effect was not investigated as detailed cost estimation methodologies and market studies would be necessary.

2.3.7. Space colonisation

Traditionally, space exploration was driven by missions from governmental agencies with scientific objectives. However, in the NewSpace age now some private actors have the capacity to reach other celestial bodies and potentially send humans to visit and colonise them. SpaceX's CEO Elon Musk revealed plans to build a self-sustaining colony on Mars by sending 1 million people there, with the ambition to make humans a multi-planetary species

[27], [80], [82]. This population is argued to be a minimum threshold to enable self-sustainability. Musk notably reported that his company was aiming to meet this objective by 2050 [83]. In a paper, he provided data on the Mars vehicle design and performance as well as launch requirements [27]. In the present study, space colonisation activities will be based on this plan, but the performances of the Mars vehicle are updated with recent information on the Starship Super Heavy. Each Mars trip was assumed to require, as reported in the reference paper, the launch of 1 ship, 5 tankers and 6 boosters, which were all modelled with adapted masses and reuse rates (see Mars vehicle in Table 3). About 10,000 trips are required to send 1 million passengers, while the same amount is required to send the 1 million tons of material reported to be necessary to build a self-sustaining colony on Mars [84]. As such, a cargo-to-person ratio (CtP) of 1:1 is considered as a baseline in this study, while early declarations of Musk mentioned a much higher 10:1 ratio. Since this parameter has significant implications for the total launch requirements, these two values were tested. This means that for each passenger flight, 1 (10) cargo flight(s) will be required, corresponding to 1 (10) ton(s) of cargo per colonist. Note that a Mars colony would need a continuous supply of cargo from Earth after the arrivals of the first colonists because a part of shipped goods will inevitably be consumable and impossible to reproduce on the colony before it becomes fully self-sustained. This continuous supply is assumed to be embedded in the CtP ratio for simplicity. In addition, a scenario in which the plan is implemented more slowly has been investigated, assuming 100,000 people on Mars by 2050. Note that a slower implementation would mean that more mass needs to be sent to supply the colony before it becomes self-sustaining, resulting in a higher average CtP ratio.

In order to meet the objective of 1 million colonists on Mars by 2050, launch rates will need to be scaled up rapidly after the first two cargo flights assumed to occur in 2024 [85]. As such, it is assumed that from 2031, 1,000 interplanetary ships each carrying 100 passengers will depart at each launch window as reported [83], along with the corresponding number of cargo flights. According to the plan, ships will be refilled on Mars and return to Earth on the next launch window to be reused. The propellant burnt for braking during re-entry and landing on Earth is neglected. Based on this plan, a minimum of 4,000 ships, 1,000 tankers and 120 boosters need to be produced to build the self-sustaining Mars colony by 2050 for a 1:1 CtP ratio. These requirements are divided by 10 if the final population is reduced to 100,000 colonists.

2.3.8. Total space activities

Since several scenarios have been investigated for some types of space activities, the estimation of the impacts of the space sector combining all these activities must be separated into different scenarios. In this regard, three scenarios for the space sector have been considered by aggregating assumptions made across different space activities that result in somewhat consistent development of the sector (Tab.6). Note that in the model, the choice of scenario affects the number of uses of stages of reusable launchers. For instance, while in the low growth scenario the Starship is used a total of 30 times before disposal for constellation activities, in the two other scenarios this number changes to 100 times from 2030. This is to be consistent with the development of EtE transportation and Mars colonisation activities in these scenarios that are operating with this high reuse rate. Furthermore, scenarios names “low”, “moderate”, and “high”, should be understood in terms of the degrees of implementation of proposed plans, not as absolute indicators of likelihood or of the level of the space sector’s growth (which would generally be considered as high even in the “low growth” scenario).

Table 6. Scenarios definition.

Scenario	Baseline	Constellations	Tourism	Moon	SBSP	EtE	Mars
Low growth	✓	✓	Low	✓	✓	-	-
Moderate growth	✓	✓	High	✓	✓	SSA-25	100,000 colonists
High growth	✓	✓	High	✓	✓	LHA	1 million colonists

2.4. Limitations

It is important to outline the limitations of the present study to ensure an adequate understanding of the meaning of the results. Due to the incompleteness of proposed plans and lack of data availability, various assumptions were necessary to model space activities, meaning that the proposed plans and systems involved are not perfectly represented. In addition, only a limited scope is considered with respect to space missions' lifecycles, which leads to underestimates. Moreover, since the SSSD did not provide full coverage of the various space systems involved in the activities described, several of them were modelled using simplifying assumptions. Datasets of the SSSD used to evaluate impacts are also based on present technologies and manufacturing processes, whose environmental performance will likely be improved over the investigated period, notably due to the expected decarbonisation of the global economy. More importantly, the impact assessment of launch events and re-entries is subjected to significant limitations that are common to all current LCA studies in which space launchers are involved (CFs not altitude dependent, inadequate description of the effects of particles such as Al_2O_3 and BC). This results in a likely severe underestimation of the impacts of launch events on climate change and ozone depletion, especially for launchers that are large emitters of particles. Therefore, it is important that the reader bears in mind these aspects when interpreting the impact assessment results of the present study.

3. Results and Discussion

3.1. LCIA results

3.1.1. Baseline activities

Baseline space activities represent 86 launches placing 127 satellites in orbit. It is found that most impacts of baseline activities are small (<0.1% of AGIs). However, impacts on ozone depletion reach 0.4% of the AGI (0.1% of the associated PB), which is significantly high considering the small number of launches described, as already highlighted by Wilson et al. when estimating impacts of the 2018 global space sector [6], [7]. However, this study finds much smaller impacts than Wilson's 2018 assessment for other impact categories. For instance, in terms of climate change, baseline activities represent merely 0.0006% of the AGI (0.0007% for 2021 activities when including constellations launches) while Wilson found 0.01%. This is likely mainly due to the consideration of a much larger scope in his analysis, including person-hours, ground segment, assembly/integration and tests operations, launch campaigns, and propellant management, handling and storage. In addition, impacts of the space segment were based on CubeSats missions (MIOS and NEACORE) that could have led to overestimates when extrapolating to average-sized satellites in Wilson's assessment, contributing secondarily to the observed differences. This reinforces the importance of remembering that the scope described by the present study is not complete when analysing impacts results. Importantly, the mass of particles emitted by baseline activities in one year is about 1,540t of Al2O3 mainly from 20 rocket launches based on solid rocket motors, and 160t of BC from 40 kerosene-fuelled rocket launches. This is a less favourable situation than the estimation of the radiative forcing of the 2012 global rocket fleet carried out by Ross and Sheaffer with 15 solid rocket motors and 25 kerosene-fuelled rocket launches out of 75. Yet, they reported that the magnitude of the radiative forcing on the stratosphere from this fleet was 16mW/m2 (70% from BC, 28% from Al2O3), about a quarter of that of global aviation on the troposphere at the time [8]. It will be roughly approximated that the baseline activities launch fleet is responsible for the same radiative forcing for comparison purposes with proposed plans.

3.1.2. Constellation activities

While less than 30 launches were dedicated to sending constellations satellites into orbit in 2021, proposed plans would lead to a sharp increase to an estimated 83 dedicated launches as soon as 2027 (Fig.2A). This is because many companies have announced that they would start the deployment of their constellations or increase their deployment pace in the coming years. Yet, the early appearance of heavy launchers with large payload capabilities significantly reduces the total number of launches, which is, therefore, not a meaningful metric as regards environmental impacts. By 2040, all modelled constellations will have completed their deployment (Fig.2B). Once all the satellites are deployed, a steady-state regime is attained in which activities are limited to the replenishment of satellites that are reaching their end of life. Note that replenishment is also necessary during the deployment phase. Overall, this results in some years with more intense activities than other. As such, after 2040, indicators related to constellation activities continue to vary widely from one year to another (Fig.2A). The maximum number of launches and payload mass delivered in one year for constellation activities are both reached in 2038 with 145 launches placing ~7.2kt of payload in orbit.

In terms of space traffic, constellation activities as modelled would lead to an extreme increase in the number of satellites in orbit from 7,840 in 2021 to about 112,000 in 2050 (x14), while the number of operational satellites would reach 92,000 (Fig.2B). The difference between these two numbers is due to the PMD times. As soon as 2029, the mass of all artificial space objects in Earth's orbit will have doubled, and the number of satellites launched every year will have overpassed 12,470, i.e. the total number of objects launched since the beginning of the space age as of 2021 [39]. From 2040 on, about 15,500 satellites on average will be launched every year, which is twice the total number of satellites in orbit in 2021. About the same number will be re-entering the atmosphere every year. Combined with the re-entry mass influx of baseline activities, we obtain that an average of 15.8kt/year of artificial objects will be re-entering consisting of 6.6kt of satellites and 9.2kt of rocket bodies. Applying the averaged survivability rates, we find that satellites will dominate the injected mass (86%) due to their high demisability and to the use of reusable launchers. Then, applying averaged material compositions, we estimate that about 3.5kt of aluminium would be re-entering every year on average from 2040 on (~27 times the natural mass influx of aluminium from meteoroids [40]). This is consistent with the value of 2.5kt found by Schulz and Glassmeier considering 75,000 constellations satellites [40]. However, as they report, the environmental consequences of these particle injections remain unknown. Then, if we assume that 100% of this injected aluminium is oxidised in Al2O3 during the high temperature demise, this leads to 6.7kt/year of Al2O3 from re-entering objects, about 3 times more than the mass injected during launch events. Note that this assumption is made here only for comparison purposes and that the actual percentage could be smaller.

Impact assessment results indicate that by the 2040s constellation activities would lead to a significant increase across all impact categories, leading to a multiplication of yearly impacts of the space sector with respect to baseline activities ranging from 2.5 (particulate matter) to 7.0 (climate change and ozone depletion). Launch events are responsible for 100% of the contribution to ozone depletion, which is consistent with previous findings [5]. In addition, the launch segment is responsible for roughly 70% of the impacts on climate change. In moderate and high growth scenarios, with the increased number of lifetime uses of reusable launch systems, impacts of constellation activities are only slightly mitigated. Regarding resource depletion, 100% of the contribution comes from the production of satellites' solar panels due to the use of germanium. However, as previously reported by Wilson [6], the selection of the horizon as the baseline for the mineral resource depletion model can have a considerable impact on LCIA results. In particular, the significance of germanium can grow by over 11 orders of magnitude. Therefore, horizon selection for measuring mineral resource depletion has become an extremely contentious issue within the space sector, due to the vast variances in results that this can cause. For this reason, the score of solar panels on this impact category was set to zero to allow the identification of the other main sources of impact. In terms of particles, by the 2030s total Al2O3 emissions of space launch activities are multiplied by 2.5 (5.5 if re-entry emissions are accounted for), while BC emissions are multiplied by 4.0. Therefore, using a simplistic proportionality approach, it can be estimated that the radiative forcing of the global launch fleet on the stratosphere would be multiplied by 3.5, meaning that it would reach more than half of that of present-day global aviation on the troposphere [14] no later than a decade from now.

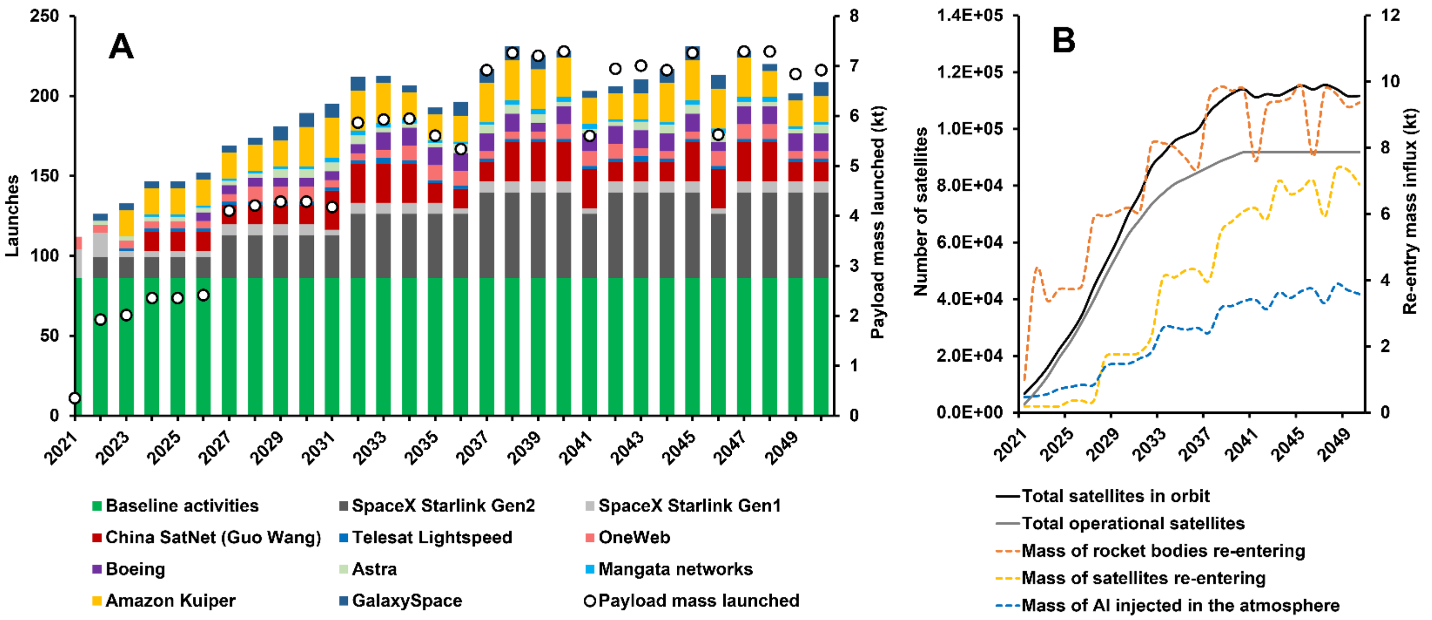

Figure 2. A: Evolution of the number of launches and of the payload mass launched of baseline and constellation activities. B: Evolution of the number of satellites in orbit and of the mass of artificial objects re-entering.

3.1.3. Space tourism

Suborbital space tourism plans would lead to very high launch rates, exceeding baseline and constellation activities in terms of the number of launches per year as soon as 2024 (Fig.3, A.1). However, the vehicles involved are typically smaller than launchers used for other activities (Tab.3), leading to much smaller impacts per launch. In fact, as modelled, environmental impacts of space tourism are dominated by those of orbital space tourism that involve much heavier vehicles. As such, in 2030, orbital tourism is responsible for 63% of the impacts of space tourism on climate change with only 20 launches/year against 800 for suborbital tourism. By 2050 the total contribution of space tourism to AGIs (of year 2010) would remain small, although ozone depletion could reach 1.4% in a high growth scenario (0.8% in a low growth scenario). However, BC emissions due to the SpaceShipTwo would be equivalent to that of all baseline activities when reaching a launch rate of ~1000/year, which could lead to much higher radiative forcing since all BC would be emitted in the stratosphere were impacts are more critical [11].

The carbon footprint of a passenger on a Virgin Galactic flight is 14tCO2eq and 34tCO2eq for Blue Origin due to higher production and manufacturing impacts. This leads to a rate of carbon footprint increase as high as 3.1tCO2eq/min for the 11min flight of Blue Origin. Accounting for BC emitted by the SpaceShipTwo would have severely increased its impacts, as found by Ross in a study [11]. Therefore, the carbon footprint of a passenger in an average suborbital space tourism flight is assumed to be about 24tCO2eq. Impact scores per passenger can be normalised using normalisation factors of the JRC [86], corresponding to one European Union (EU) citizen over one year. Using this method, the normalised carbon footprint obtained is 2.6 EU citizens. More concerning is the passenger footprint related to ozone depletion, which is equivalent to that of several hundreds to a thousand of EU citizens (Fig.4).

In terms of orbital space tourism, two missions (one past, one planned) assumed to be typical have been analysed: a flight in Earth orbit based on the Inspiration4 mission (Falcon 9, 4 passengers), and a flight around the Moon based on the dearMoon mission (Starship Super Heavy, 10 passengers). Based on this, although different launch vehicles are used, it can be estimated that the carbon footprint of a passenger in an orbital tourism flight is about 660tCO2eq and 1670tCO2eq in a Moon tourism flight, in addition to several hundred kg of BC emitted per passenger. Impacts on air acidification and ozone depletion are particularly alarming, reaching thousands to hundreds of thousands of equivalent EU citizens over a year (Fig.4).

3.1.4. Moon missions and SBSP

Over the period from 2022 to 2035 that was based on scheduled missions, the launch segment of Moon plans would create impacts equivalent to between 22% and 40% of the impacts of baseline activities depending on the impact category and flow indicator. These shares are doubled after 2035. However, the space segment, which was excluded from the scope for Moon missions, is likely to be responsible for higher impacts with crewed flights and exploration missions (rovers, bases, …) than with the Earth-orbiting satellite missions that mainly compose baseline activities.

Furthermore, the impacts of the launch segment of China and the UK’s plans for SBSP would be responsible for yearly impacts that are roughly equivalent to those of baseline activities. However, the production of space power satellites is likely to be a major environmental hotspot of these projects given the importance of solar panels in satellites LCIA results (e.g. 53% on climate change with the model of Table 4). Consequently, comparisons between activities should be done with care. The mass of BC emitted every year is twice that of baseline activities mainly due to the intense use of kerosene-fuelled LM 9, but also of methane-fuelled Starship Super Heavy.

3.1.5. Earth-to-Earth transportation

Even in the most conservative scenario, the development of a rocket-based transportation system for point-to-point travel on Earth would constitute a surge in space activities (Fig.3, B.1). Normalised results are outlined in Table 7.

In the SSA-25 scenario, by 2050 the contribution of EtE to climate change would reach 0.2% of the AGI (of 2010) and 1.3% of the associated PB. More importantly, ozone impacts would reach 227% of AGIs and 71% of the PB, although these impacts are more uncertain. While this scenario is conservative, it would already lead to concerning environmental impacts, exceeding by far those of baseline and constellation activities. Slightly higher levels of contribution would be reached as soon as 2032 according to the LHA scenario, even though it is based on a forecast that UBS described as conservative [81]. Under the SSA-100 scenario, the contribution of EtE to ozone depletion would be particularly alarming, reaching more than 9 times the AGI and almost 3 times the associated PB. In both SSA scenarios, BC emissions would be two orders of magnitude higher than those of baseline activities, potentially leading to a radiative forcing on the stratosphere tens of times that of present-day global aviation if Ross and Sheaffer estimations are simplistically multiplied [8]. Furthermore, the LHA scenario would make the contribution of EtE to climate change (without BC) comparable to present-day aviation-CO2 and make its impacts on ozone depletion extremely high. BC emissions would be even more critical. In its 20 years of activity between 2030 and

2050, under the SSA-100 scenario EtE would consume 1.2% of the residual global carbon budget from 2020 for a 50% chance to limit warming to 1.5°C, and 1.6% in the LHA scenario.

Furthermore, the carbon footprint of a passenger on a typical EtE rocket flight is estimated to be at least 15tCO2eq, in addition to 3.7kg of BC. While the high number of passengers (1000) enables an important reduction of the footprint, it is still much higher than those of typical long-haul commercial airline flights this transport solution seeks to replace (e.g. ~1.5-2tCO2eq for a one-way flight from Los Angeles to Shanghai in economy class, and about double in business class). Assuming ~30min flights as announced by SpaceX, this means that each passenger increases its carbon footprint at a rate of about half a ton of CO2 per minute. In addition, the contributions of a passenger to air acidification and ozone depletion are very concerning (Fig.4).

3.1.6. Mars colonisation

Even under the hypothesis of a 1:1 CtP ratio, plans for Mars colonisation would lead to a tremendous increase in launch activity and in associated environmental impacts. The average number of launches per year would reach about a fifth of that of the LHA scenario of EtE transportation (Fig.3, C.1), which is consistent since EtE transportation flights likely need to be common for an intense Mars colonisation to occur. Except during the production of interplanetary ships assumed to occur between 2026 and 2032, environmental impacts are concentrated in the 13 Mars launch windows. From 2031 onwards, at every year of a launch window (every ~2 years), with a 1:1 CtP ratio, environmental impacts of Mars colonisation activities would reach high levels (2-3% of PBs) on most impact categories, and very high levels for ozone depletion (144% of the PB) (Tab.7). The impact on climate change would reach 2.8% of the PB, which means that about every 2 years, the same percentage of total anthropogenic greenhouse gases emissions that the planet can cope with would have to be dedicated to this endeavour. In addition, it would consume 0.5% of the 1.5°C global carbon budget. About 4,600 tons of BC would be emitted at each launch window, roughly 30 times the emissions of baseline activities. With a 10:1 CtP ratio, impacts would reach very high levels on most impact categories (13-17% of PBs) and extremely alarming levels on ozone depletion (~8 times the associated PB). Considering a smaller colony of 100,000 people in 2050, these impacts would be divided by 10, although a higher CtP ratio would likely be required. Consequently, this would still lead to very high results.

Then, it is estimated that the carbon footprint of a typical Mars colonist would be at least 1,900tCO2eq assuming a 1:1 CtP ratio (+460kg of BC), and at least 10,500tCO2eq assuming a 10:1 CtP ratio (+2500kg of BC). This is equivalent to 207 and 1,140EU citizens over one year, respectively (Fig.4).

Table 7. Launch rates and contribution to AGIs and PBs of Earth-to-Earth transportation (year 2050) and Mars colonisation (typical launch window year) across different scenarios.

	Earth-to-Earth transportation						**Mars colonisation (1 million colonists)**			
	SSA-25		**SSA-100**		**LHA**		**CtP 1:1**		**CtP 10:1**	
	AGI	**PB**	**AGI**	**PB**	**AGI**	**PB**	**AGI**	**PB**	**AGI**	**PB**
AA[4]	2.95%	1.13%	11.81%	4.54%	18.69%	7.18%	6.15%	2.36%	33.83%	13.00%
CC	0.16%	1.33%	0.62%	5.32%	0.99%	8.42%	0.31%	2.60%	1.68%	14.32%

OD	227.02%	70.89%	908.07%	283.56%	1437.52%	449%	460.01%	143.65%	2530.04%	790.05%
PO	0.14%	1.54%	0.58%	6.15%	0.91%	9.73%	0.23%	2.46%	1.27%	13.52%
RD	0.31%	-	1.23%	-	1.95%	-	0.16%	-	0.89%	-
BC emissions / baseline	x140		x540		x860		x290		x1580	
Launches/day	16		65		103		33		181	
Cities Connected daily	4		8		10		N/A		N/A	

[4] AA = air acidification; CC = climate change; OD = ozone depletion; PO = photochemical oxidation; RD = resource depletion; BC = black carbon.

3.1.7. Total space activities

The total impacts of space activities within the scope of the study are approximated by aggregating the impacts associated with the activities considered here since they are likely to be the main contributors. As such, the sustainability of the space sector can be assessed (within the scope considered) by comparing the total impacts obtained to AGIs and PBs, depending on the different scenarios of implementation and degrees of success of proposed plans as defined in Table 6. Results are outlined in Table 8.

In the low growth scenario, in 2050 the contribution of space activities to AGIs would be small (<0.2%) for most impact categories. However, the contribution of the space sector to the AGI on ozone depletion would reach 6%, a level that could already trigger attention from ozone protection schemes. Regarding the relative contribution of each activity to total impacts over the period 2022-2050, constellation activities would be responsible for most of the impacts (49% to 58% depending on the impact category), followed by baseline activities (10% to 24%) and SBSP (12% to 17%) (Fig.3, A.2). Total $Al2O3$ and BC emissions would be multiplied by 6.5 and 7.3 with respect to baseline activities no later than the 2030s, which may make rocket radiative forcing on the stratosphere 1.1 higher than that of present-day global aviation on the troposphere. The re-entering mass from space tourism, Moon missions and SBSP activities combined would be very small compared to those of baseline and constellations activities (~1%) discussed in section 3.1.2.

Conversely, in the moderate growth scenario, activities of EtE transportation would be responsible for most of the impacts (~75%) followed by Mars colonisation activities (~12%) (Fig.3, B.2). They do not contribute to $Al2O3$ emissions due to the absence of this compound in the exhausts of launchers involved in these activities but do contribute to BC emissions, which are multiplied by 580 and would potentially have extreme effects on the atmosphere's radiative balance. Due to the very high launchers reuse rates involved in this scenario, the impacts of the production of launcher components become negligible with respect to that of propellant production and launch events. This also makes the relative contribution of EtE transportation and Mars colonisation activities to resource depletion smaller than to other impact categories (Fig.3, B.2). The contribution of space activities to AGIs would reach high levels of air acidification (5%) and very high levels of ozone depletion (341%). The contribution on climate change, although moderate (0.2% of the AGI) would reach 1.9% of the associated PB. In this regard, about 0.4% of the 1.5°C global carbon budget would be consumed by space activities. With a 10:1 CtP ratio for Mars colonisation activities, levels of contribution would be almost doubled while consumption of the global carbon budget would reach 0.6%.

Then, in the event that all proposed plans are fully implemented as depicted by the high growth scenario, the contribution of space activities to AGIs would reach high levels for all impact categories, with contributions as high as 2320% for ozone depletion or 31% for air acidification, again mainly from EtE transportation (~75%) (Fig.3, C.2). BC emissions are multiplied by 1160. Space activities would consume 2.1% of the 1.5°C global carbon budget. Importantly, contributions to PBs would reach alarming levels (12% to 725%). With a 10:1 CtP ratio for Mars colonisation, it would reach even higher levels (24% to 1241%).

Lastly, if the effects of NOx produced during re-entry are accounted for, LCIA results are increased substantially across all impact categories except resource depletion (Tab.9). The main contributors are heavy upper stages like the Starship, which produces an estimated 21t of NOx at each re-entry, increasing the lifecycle impacts of the Starship Super Heavy on climate change by 14% and on ozone depletion by 23%. Accounting for BC emitted during launch with an aviation-based CF also increases significantly the impacts on climate change (28-36%) although this approach is likely to poorly represent actual impacts like those reported by Ross and Sheaffer, as was commented in this analysis.

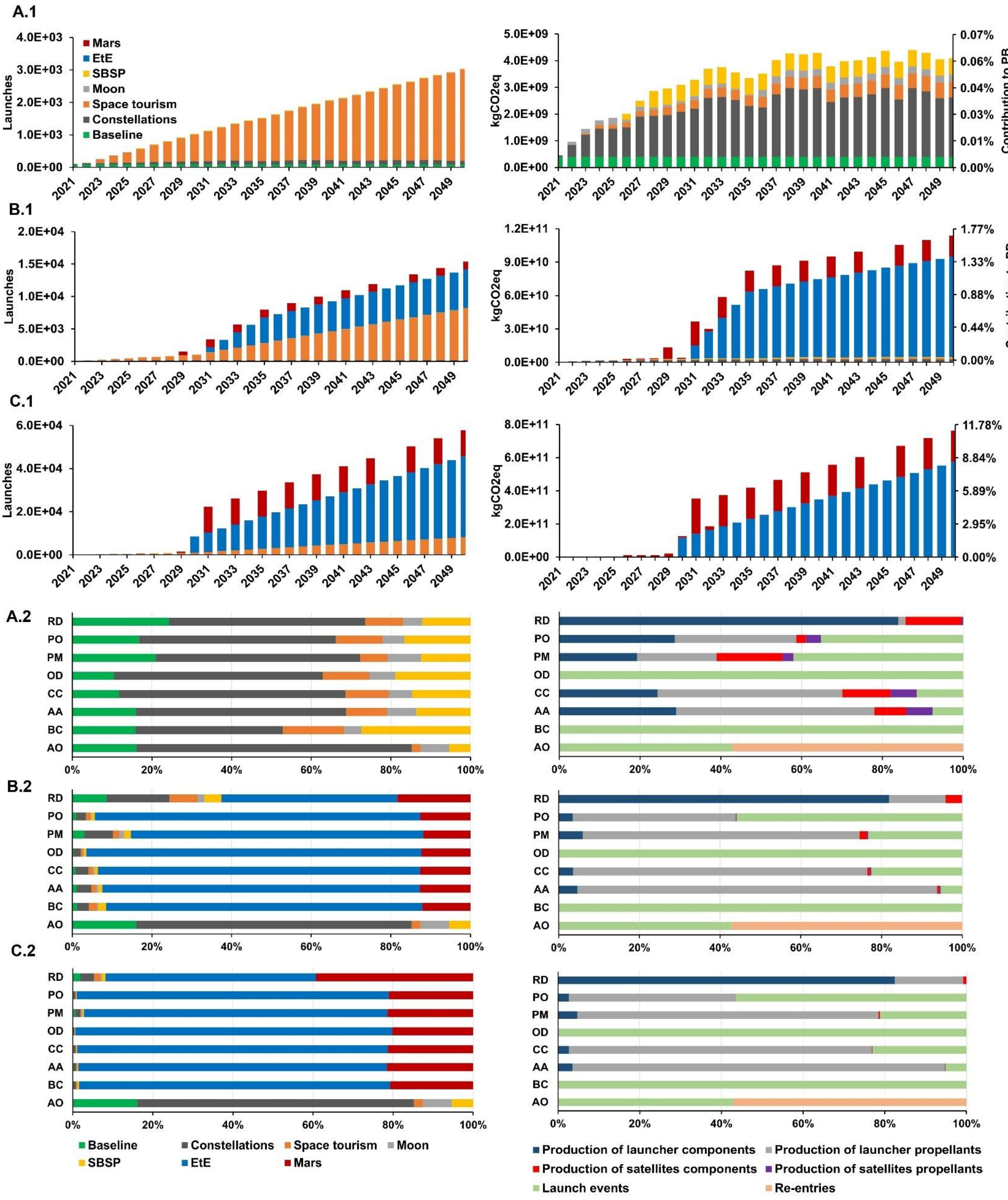

Figure 3. Evolution of launch rates and impacts on climate change (A.1, B.1, C.1). Contributions of activities and lifecycle steps to total impacts and Al2O3 and BC emissions over the 2022-2050 period (A.2, B.2, C.2). (A) Low growth scenario; (B)

moderate growth scenario; (C) high growth scenario. AO = Al2O3 emissions; BC = black carbon emissions; AA = air acidification; CC = climate change; OD = ozone depletion; PO = photochemical oxidation; RD = resource depletion.

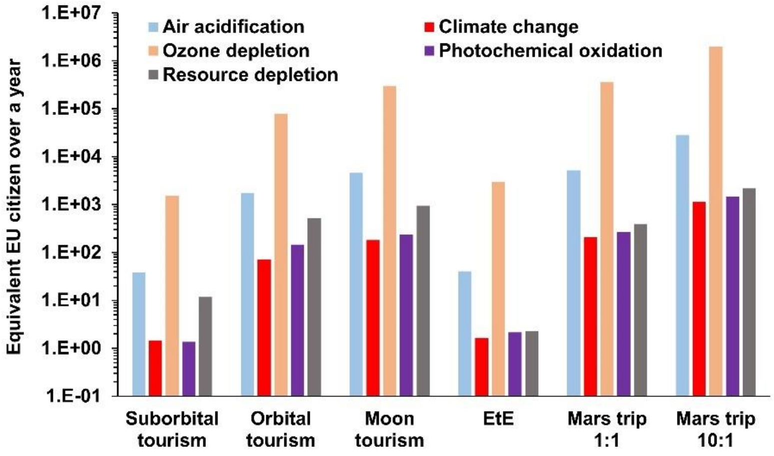

Figure 4. Environmental footprints of passengers in typical space travel flights normalised by those of an EU citizen over a year. Models of suborbital, orbital and Moon tourism based on current flights; models of EtE and Mars trips based on speculative objectives.

Table 8. Estimated environmental sustainability of 2050 space activities in 3 scenarios of implementation of proposed plans.

Impact category	Unit	Low growth			Moderate growth			High growth		
		LCIA	AGI	PB	LCIA	AGI	PB	LCIA	AGI	PB
AO	kg Al2O3	1.21E+07	-	-	1.21E+07	-	-	1.21E+07	-	-
BC	kg BC	1.19E+06	-	-	2.80E+07	-	-	1.86E+08	-	-
AA	kg SO2eq	1.94E+07	0.16%	0.06%	4.6E+08	3.75%	1.44%	3.1E+09	25.05%	9.63%
CC	kg CO2eq	4.10E+09	0.01%	0.06%	1.1E+11	0.20%	1.68%	7.6E+11	1.32%	11.25%
OD	kg CFC-11eq	9.58E+06	5.70%	1.78%	4.7E+08	279.33%	87.23%	3.2E+09	1903.84%	594.51%
PM	kg PM10eq	1.47E+07	-	-	1.7E+08	-	-	1.1E+09	-	-
PO	kg NMVOCeq	1.58E+07	0.01%	0.06%	5.0E+08	0.18%	1.92%	3.4E+09	1.21%	12.95%
RD	kg Sbeq	6.15E+05	0.14%	-	2.21E+06	0.50%	-	1.06E+07	2.41%	-

Table 9. Increase in total LCIA results of scenarios when accounting for the effects of NOx produced during re-entry and of BC emitted during launch (aviation-based CF).

Sensitivity to	Impact category	Low growth	Moderate growth	High growth
Re-entry NOx	AA	+6%	+22%	+23%
	CC	+5%	+15%	+15%
	OD	+12%	+22%	+22%
	PM	+2%	+19%	+20%
	PO	+10%	+29%	+29%

Launch BC	CC	+36%	+29%	+28%

3.2. Discussion

3.2.1. Implications

Results suggest that the development of space activities over the period 2022-2050 consistent with the low growth scenario would lead to small impacts, although ozone depletion could be of concern – but has high uncertainties attached. However, it should be reminded that apart from ozone depletion, calculated impacts are underestimates as discussed in Section 2. Even if the increasing impacts of the space sector are constrained to small levels, space companies and institutions are likely to be subjected to ever-growing pressure in the future to reduce their environmental footprint. Yet, proposed plans and current trends in the sector are clearly pushing against this reduction through a significant increase in activities. Moreover, the high magnitude of the effect of particles on the radiative balance of the atmosphere (comparable to the influence of present-day global aviation) is uncertain, but if confirmed, it would seriously undermine the sustainability of plans investigated in this scenario and trigger regulatory responses. As such, even in this scenario that does not include the most speculative plans, large efforts to reduce the environmental impacts per kg of payload sent into orbit would be required to mitigate the probable increase in the total environmental impacts of the space sector. There are various ways to attempt to reduce the impacts of engineering systems in general, as explored in [87], but this needed discussion for the space sector is left to dedicated studies. Furthermore, the social acceptance of space activities, especially those with little actual or perceived contribution to the larger society, may be undermined (aspect further discussed in Section 3.2.3.). In this regard, it would surely be beneficial to limit activities with high environmental footprints and low added value for the larger society, and have more activities contributing positively to sustainability, like climate and environmental monitoring services, early-warning and disaster relief systems, or satellite data supporting mitigation and adaptation.

In addition to environmental impacts on the Earth system, it is likely that the development of constellation activities as described in all scenarios, including the low growth scenario, would lead to important issues regarding space debris or interference with ground-based astronomy [16], [17], [42], [44], [88], which were not considered in the present study. In this respect, reviewed papers expressing concerns over the effects of the introduction of constellation satellites on the space debris population considered no more than several thousand satellites, while the present study found that proposed plans could lead to an in-orbit population of about 112,000 satellites by 2050. Although a detailed study would be necessary to assess properly the implications of such a large population, based on the conclusions of the reviewed studies it can be safely affirmed that a steep increase in collision rate and in the debris population would be observed, implying that current policies and modelling capabilities would need to be rapidly revised and adapted. Furthermore, if solutions of debris mitigation and space traffic management were ultimately able to manage the issue of space debris, issues of interference with astronomical observations would still need to be addressed. Moreover, if future studies identify the injection of particles in the atmosphere due to re-entries as an environmental hotspot of space missions, alternatives to spacecraft deorbitation in Low Earth Orbit (LEO) will need to be found to mitigate space debris, such as in-orbit servicing.

More intense development of space activities including the partial implementation of EtE transportation and Mars colonisation plans, as depicted by the moderate growth scenario, would lead to concerning levels of environmental impacts. As illustrated by its contribution to PBs (Tab.8), the space sector would become a significant actor in environmental change. In this regard, in the strive towards making the environmental footprint of human activities fit within PBs, the space sector would be conflicting with activities associated with basic human needs including nutrition, sanitation, education or energy production. Consequently, it is clear that the space industry would undergo significant regulatory and social pressures to reduce its environmental footprint. In particular, the launch industry would likely go under intense scrutiny in the name of climate or ozone protection, which could lead to regulations on some rocket exhaust components. If confirmed, the extreme magnitude of the effects of particles emitted by launchers would make this even clearer.

Regulatory action and social pressures would be even more severe if proposed plans are implemented at their full extent (high growth scenario), because impacts of space activities would reach highly unsustainable levels. Like in the moderate growth scenario, it is likely that these external reactions would limit the development of space activities well before it ever reaches this level of development.

To reduce these impacts, given the prominence of the role of propellant production on climate change (75% for the Starship Super Heavy when high reuse rates are assumed, with somewhat equivalent contributions from LOX and methane), the use of low carbon fuels like biomethane, synthetic methane, or low carbon hydrogen could seem to be an effective mitigation option. In particular, the production of synthetic methane (power-to-gas) could also ensure the production of low carbon LOX as a by-product of the electrolysis reaction, which might explain why SpaceX revealed plans to use this solution to produce its rocket propellants [89], [90]. Nevertheless, this approach presents important challenges in terms of technology readiness and cost, and can provide environmental benefits only when low carbon electricity is used for the electrolysis and for the direct air capture (DAC) of CO2 [91], and when hydrogen and methane leakages are effectively constrained to small levels [92], [93]. Importantly, scaling up the production of low carbon hydrogen and DAC to reach global climate targets, as well as the low carbon electricity they need, already presents significant challenges without the contribution of intense space activities in the demand (like the amount of energy and materials required, materials criticality, and supply bottlenecks) [94], [95], [96]–[99]. Alternatively, biomethane could be employed, but it also presents significant challenges on a large scale due to the climate effects of land-use change and the competition with global food production and ecosystem restoration efforts [100], [101]. Yet, these issues of scale would become relevant for such intense EtE transportation and Mars colonisation plans as they are envisioned. For instance, if synthetic methane is used its demand in DAC would reach 2% to 15% of the 980 Mt CO2 assumed to be captured in 2050 in a net-zero scenario by the International Energy Agency (IEA) [102], although such a scale-up (0.01Mt CO2 in 2021) is subjected to significant challenges already discussed. To illustrate this scale issue further, the demand for low carbon fuel alternatives in moderate and high growth scenarios has been computed and compared to the global demand in scenarios of the IEA [103], [104]. For both options investigated (LOX/biomethane and LOX/ low carbon LH2), results indicate that space activities would either enter in severe competition with other sectors in their mitigation efforts, or require a significant increase in supply (Tab.10).

Table 10. Demand in low carbon fuels of EtE and Mars colonisation activities compared to the global demand in IEA projections based on stated policies or sustainable development scenarios (both in 2040). Numbers in parenthesis indicate the share of the demand in the transport sector. The mass of hydrogen required is based on an

assumed LOX/LH2 propulsion alternative and was obtained through a proportional conversion with respect to the respective energy contents of 55 MJ/kg for methane and 120 MJ/kg for hydrogen.

	Biomethane			Low carbon hydrogen (electrolysis + CCUS[5])		
	Mass required (Mt)	Stated policies	Sustainable development	Mass required (Mt)	Stated policies	Sustainable development
Moderate growth	7.4	8% (23%)	3% (14%)	3.4	3% (14%)	1% (6%)
High growth	52.0	49% (141%)	18% (83%)	23.8	17% (85%)	5% (34%)

[5] Carbon capture, utilisation, and storage

Furthermore, regardless of the propellant combination used, climate impacts due to launches and re-entries would be much more difficult to mitigate deeply due to the emission of non-CO2 climate forcers (BC , Al2O3 and other particles, water vapor, NOx) and their interaction with the radiative balance of the atmosphere [8] or with cloud formation that could have significant effects [8], [18], as is already seen in aviation [14]. For supersonic and hypersonic transport aircraft, these effects were already found to increase considerably with the flying altitude and even to become dominant [15], [105]. Moreover, ozone depletion due to the emissions of ozone-destroying compounds (ClOx, HOx, NOx) by all propellant combinations would also be difficult to mitigate, which is critical given the very high levels of impacts estimated in this study. Additional noise pollution like from sonic booms would also need to be carefully monitored and mitigated, especially for EtE transportation where proximity to population centers might be expected, an issue already driving designs of supersonic transport jets [106]. Consequently, results indicate that achieving such intense EtE transportation and Mars colonisation plans using conventional chemical rocket technology without seriously harming the Earth environment would require tremendous impact mitigation efforts and technological breakthroughs unlikely to occur within such short timescales of implementation. Combined with the previously discussed environmental impacts, these structural, physical and social constraints illustrate the existence of environmental limits to the development of proposed space activities, as suggested in a previous study [13].

3.2.2. Making humans a multiplanetary species: the question of environmental sustainability

In particular, this implies that the intense expansion of humans in space envisioned by some private actors may well be incompatible with the global endeavour towards ensuring a good life for all within PBs. However, it should be noted that sustainability issues on Earth are one of the very reasons used to justify Mars colonisation activities [107]. In this respect, it is argued to be like “insurance for life”, in the sense that an investment from the Earth’s economy in space colonisation activities is necessary so that life would be preserved in case something happened on Earth. Yet, advocates of this argument have consistently failed to acknowledge that an environmental investment is also necessary, in the sense that space colonisation activities consume energy and resources on Earth and degrade its environment. In this regard, the critical aspect of environmental impacts on Earth is also absent from ethical considerations in the academic literature (e.g. [107]). However, the present study indicates that this environmental cost could be very high and hamper humans efforts to achieve sustainability on Earth. This could actually undermine the social acceptability of Mars colonisation plans even more than the economic cost, which is generally assumed as the major issue [108]. As such, environmental sustainability appears as an additional constraint to technology and economic factors in achieving a multi-planetary civilisation, making it even more difficult. To be fully consistent with one of its main objectives of preserving life, any intense space colonisation scheme should include at minimum a thorough assessment of its environmental impacts combined with a mitigation plan. Yet, environmental sustainability is not mentioned in any referenced document and presentation of the reference Mars colonisation plan [27], [85], [109], [110]. In particular, it is worth noting that the choice of methalox as the propellant of the Mars vehicle was based on pure technological and economic factors, while no environmental considerations were included [27]. For instance, kerosene, a much larger BC emitter than methane (x25 on a /kg of propellant basis in the present model), was considered a potential fuel candidate. Had it been chosen based on superior technical or economic performances, it would have had serious implications on the environmental impacts of all activities in which the Starship Super Heavy vehicle and its derivations are involved, including constellations, orbital tourism, EtE transportation and Mars colonisation. This illustrates the importance of considering the criterion of environmental performance during space systems design, particularly for the choice of a rocket propellant due to the large associated environmental implications, which is even more critical if very high launch rates are planned.

3.2.3. Recreational space travel and environmental inequality

Environmental inequality refers to the unequal distribution of responsibilities and vulnerabilities to environmental change with respect to socio-economic factors. These inequalities are particularly severe regarding climate change and income distribution, as lower-income groups have been shown to contribute least to climate change while being disproportionately affected by its consequences [111], [112]. For instance, Chancel and Piketty [113] have estimated that carbon emissions of the world richest 1% are emitting about 100 times more than the poorest 10%. As a consequence, there is a growing interest to incorporate concepts of environmental and climate justice in climate policies, as highlighted by the Intergovernmental Panel on Climate Change Working Group III in the 6th Assessment Report [114].

In this respect, regardless of the importance of their contribution to AGIs and PBs, space activities consisting of providing some form of experience or service to a passenger raise important issues of environmental inequalities by combining high environmental footprints per passenger and high economic inaccessibility. Ticket prices of recent suborbital space tourism flights ranged between 450k$ and 28 million $, which place their potential viable customers in the ultra-high net worth individuals (UHNWI) wealth band, i.e. the wealthiest 0.0025%. Although very high, the calculated carbon footprint of a suborbital space tourism flight is smaller than the daily emissions of some billionaires [115], meaning that it is comparable to the carbon footprint of most polluting ultra-luxury experiences such as private jet transportation or superyacht trips. However, the calculated impact on the ozone depletion category is likely to have no close equivalent even among ultra-luxury experiences. Regarding orbital tourism, ticket prices of recent flights were reported to be 55 million $, meaning that their potential viable customers are in the few firsts top percent of the UHNWI wealth band, i.e. the wealthiest 0.0001%. The calculated environmental footprints per passenger are extremely high (Fig.4) and have certainly no close existing equivalent even among ultra-luxury experiences in this respect. Since it is also one of the most expensive ultra-luxury experiences, orbital tourism likely constitutes the most extreme existing activity in terms of climate and environmental inequalities.

Moreover, rocket EtE transportation aims at providing a faster solution than long-haul airplane flights, with announced fares (about 1k$/ticket) that are comparable to those of their business classes. However, aviation has already long been identified as critical in terms of climate inequality. For instance, Gössling and Humpe [116] estimated that half of the CO2 emissions from commercial aviation were emitted by 1% of the world population, while only 2% to 4% of global population flew internationally in 2018. Consequently, rocket EtE transportation would be even more critical than aviation in terms of environmental inequalities since impacts per passenger were estimated to be significantly higher than those of typical long-haul airplane flights.

Regarding Mars colonisation activities, the calculated environmental footprints per passenger are extremely high (Fig.4). In terms of cost, a ticket's price is planned to be less than 500k$, possibly reaching 100k$. However, for the first colonists, the trip to Mars would likely be a very hard, dangerous, life-threatening experience. Consequently, they do not really compare to the tourism activities or transport services previously discussed that are used for leisure or business motives. Nonetheless, the objective of the plan being to ultimately build a self-sustaining colony of 1 million people, most passengers would travel and live in much better conditions and with less risky odds than the early colonists. Consequently, as travelling to Mars become more common, the lines separating it from conventional travel on Earth might be increasingly blurred, leading to criticisms related to environmental inequalities.

4. Conclusion

The results of this study imply that environmental impacts could be a key limiting factor for the development of some space activities, and strongly suggest that there is a pressing need to include environmental considerations in addition to technical and economic analyses in space projects definition and space systems design.

Lastly, the various assumptions and uncertainties involved in this study demonstrate that more research is needed to evaluate the significance of the impacts of future space activities. In this regard, the lack of data on altitude-dependent effects of non-CO2 climate forcers and ozone-destroying compounds from launchers and satellites is a particularly prominent issue. Results presented in this study need to be confirmed by future work using more detailed and comprehensive descriptions of future activities and space systems design, as well as more precise modelling of their impacts. Studies investigating what policies would be appropriate to help make space activities compatible with planetary boundaries are also needed.

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