Environmental sustainability of future proposed space activities

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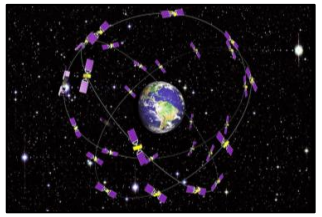
ESA Clean Space Industry Days
12/10/2022

Context & Objectives

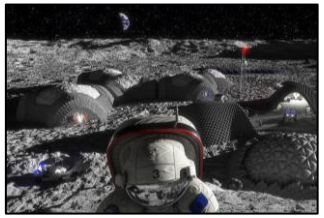
1. New paradigm enabling the development of new space activities

...leading to heightened promises and expectations that shape our shared narratives of the future

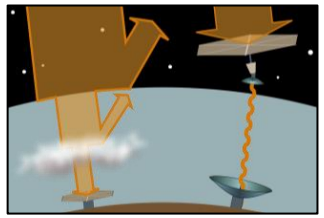


Large constellations of satellites
Global broadband connectivity for all!

Space tourism
Space is for all humanity!



Lunar missions
We are going back there to stay and prepare Mars!



Space-based solar power
Clean energy to help meet our climate targets!

Earth-to-Earth transportation
Everywhere on Earth in under an hour!

Mars colonisation
Planet B!

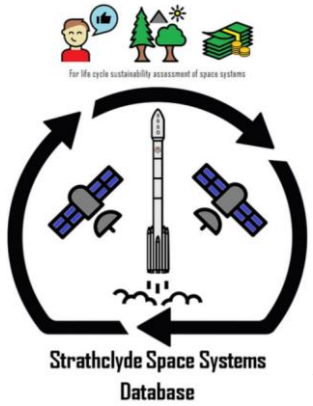
2. Previous research on the environmental impacts of space activities

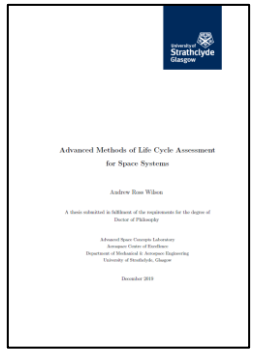
...leading to serious doubts on the industry's capability to live up to its promises

Miraux, L. (2021). Environmental limits to the space sector's growth. *Science of The Total Environment*, *806*, 150862.
https://doi.org/10.1016/j.scitotenv.2021.150862

3. Space-specific Life Cycle Sustainability Assessment database being developed

...making possible an independent, rough order of magnitude assessment of the impacts of these activities



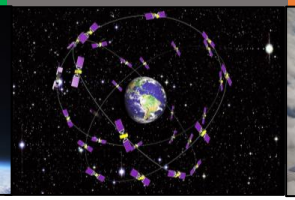
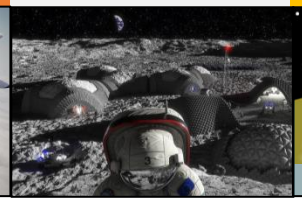
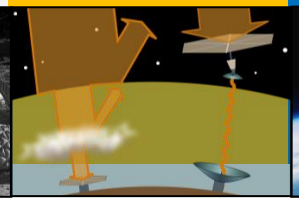


Wilson, A. R. (2019). Advanced methods of life cycle assessment for space systems.
https://stax.strath.ac.uk/concern/theses/rj430454t

Evaluation of the environmental impacts of future proposed space projects

- LCA framework
- Aligned with global sustainability targets timeline (2050)
- Based on real proposals and space systems
- Focusing on large-scale activities having the potential to drive impacts
- **Thought experiment, not predictive**
- Results analyzed with a "systems lens"

Scope

		BASELINE	CONSTELLATIONS	SPACE TOURISM	MOON MISSIONS	SBSP	EARTH-TO-EARTH TRANSPORTATION	MARS COLONISATION
								
	[1] Flow indicator							
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

Methodology

SPACE ACTIVITIES
2021-2050

BASELINE	CONSTELLATIONS	SPACE TOURISM	MOON MISSIONS	SBSP	EARTH-TO-EARTH TRANSPORTATION	MARS COLONISATION

Literature, roadmaps, public statements, market analyses, assumptions…

Activities LCI: launchers and payloads, launch rates, timeline,…

LAUNCH SEGMENT

LCI available in SSSD

- *Ariane 62-64*
- *Atlas V*
- *Delta IV*
- *Falcon 9*
- *Falcon Heavy*
- *Long March 3B*
- *Soyuz-FG*

LCI from literature and SSSD

- *Starship*
- *Mars vehicle*
- *Long March family*
- *SpaceShipTwo*
- *New Shepard*
- *New Glenn*
- *Vulcan Centaur 6*
- *SLS Block 1/1B/2*

Literature: staging, structural mass, propellant type and mass, utilisation regime, payload capacity
SSSD: generic launcher components model + propellant LCI and launch characterization factors

SPACE SEGMENT

LCI from literature and SSSD

Starlink satellite

Literature: mass breakdown per component+propellant
SSSD: component and propellant LCI

Proxy baseline activities satellite
Mass scaling (avg mass: 617kg)
Xenon

Proxy constellation satellite
Mass scaling (tailored to constellation data)
Xenon/krypton (tailored to constellation data)

LCIA from SSSD + Excel model → Comparison to Annual Global Impacts (2010) and Planetary Boundaries

Strathclyde Space Systems Database

Modeling of space-specific phases

PHASE	RELEVANT PHYSICAL QUANTITY / PHENOMENON	CHARACTERISATION IN THIS STUDY
Launch	N2, CO2, CO, H2 emissions	Ground-based
	H2O emissions	CC: aviation-based
	NOx emissions	AA, PM, PO: ground-based CC: aviation-based OD: stratosphere-based estimate
	ClOx, HOx, HCl emissions	OD: stratosphere-based estimate
	Al2O3 emissions	Flow indicator
	Black carbon emissions	Flow indicator
Orbit	Number of satellites in orbit	Flow indicator
	Number of operational satellites in orbit	Flow indicator
Re-entry	Mass of rocket bodies re-entering	Flow indicator
	Mass of satellites re-entering	Flow indicator
	Mass of aluminium (and Al2O3) emitted upon re-entry	Flow indicator
	NOx produced in shock waves	Same as launch (sensitivity)

CC = Climate Change
AA = Air Acidification
PM = Particulate Matter
PO = Photochemical Oxidation
OD = Ozone Depletion

Baseline activities

= 2021 space activities excluding constellations and tourism

LAUNCH SEGMENT:

- Actual launchers
- 112/133 launches covered but close to 100% payload mass

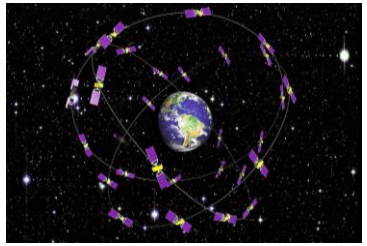
SPACE SEGMENT:

- Proxy satellites
- 5 spacecraft models / mission (1:1 mass ratio)
- Assumed to remain constant over 2021-2050 period (for reference only)

	AIR ACIDIFICATION [kg SO2eq]	CLIMATE CHANGE [kgCO2eq]	OZONE DEPLETION [kg CFC-11eq]	RESOURCE DEPLETION [kg Sbeq]	AL2O3 EMISSIONS [kg]	BC EMISSIONS [kg]
TOTAL BASELINE	2.7E+06	4.3E+08	8.1E+05	1.4E+05	1.5E+06	1.6E+05
ANNUAL GLOBAL IMPACTS (AGIs)	0.022%	0.001%	0.482%	0.031%	-	-
PLANETARY BOUNDARIES (PBs)	0.008%	0.006%	0.151%	-	-	-

≈ **1/4th of global aviation radiative forcing of 2009**
(based on Ross et al. findings)

Constellations: modeling

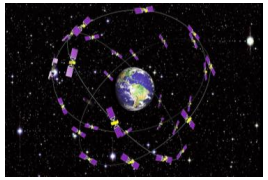


Plans of 10 heaviest constellations

~92,000 satellites (36k tons) when fully deployed

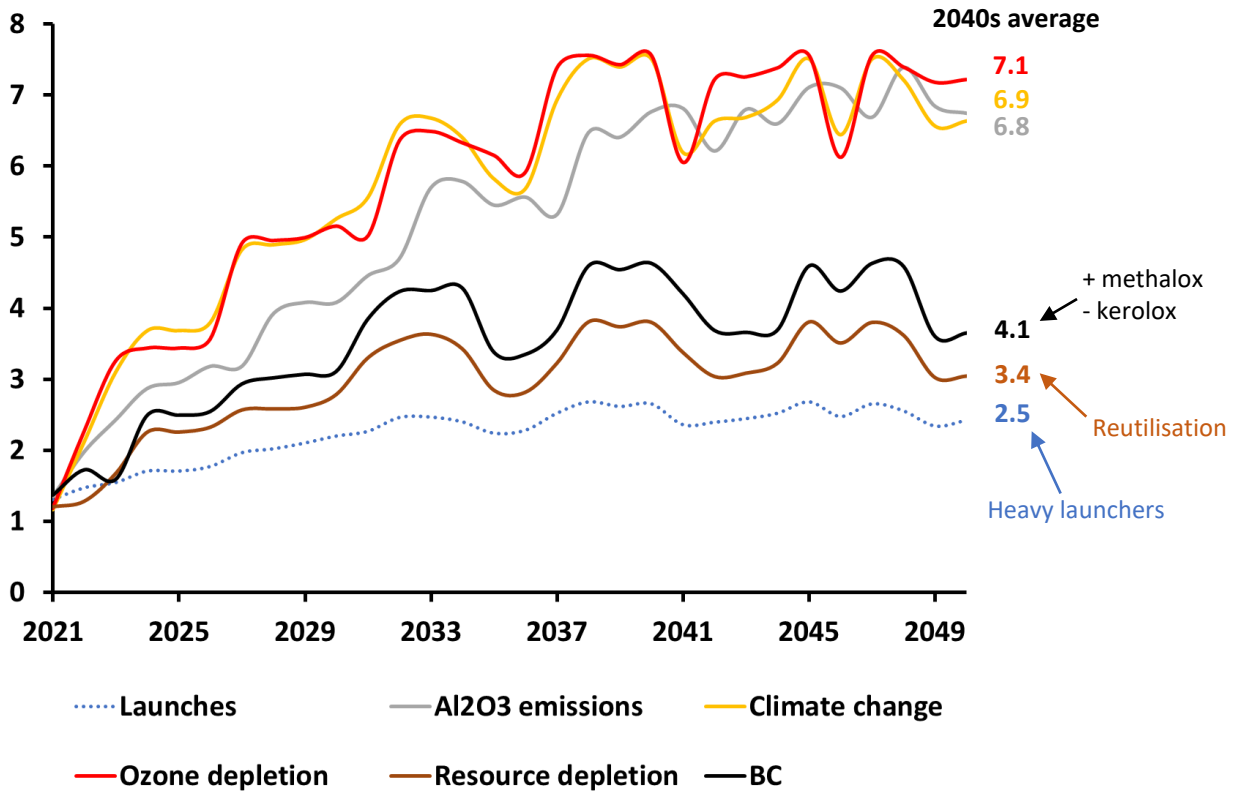
NAME	N° SATS	N° SATS ALREADY IN ORBIT	STARTING DATE	FULL DEPLOYMENT DATE	LAUNCHER	LAUNCHER CAPACITY (T)	AVERAGE SATELLITE MASS (KG)	SATELLITE PROPELLANT	SATELLITE LIFETIME (Y)	PMD TIME (Y)
SpaceX Starlink Gen2	30 000	0	2022	2040	Starship Super Heavy	100	850	Krypton	5	1
SpaceX Starlink Gen1	10220	1780	2021	2030	Falcon 9 (2022 only) Starship Super Heavy	100	260	Krypton	5	1
China SatNet	12 992	0	2024	2034	Long March 5	25	260	Xenon	7	2
Telesat Lightspeed	1371	2	2023	2033	New Glenn	45	700	Krypton	10	2
OneWeb	6154	218	2021	2030	Falcon 9	8	150	Xenon	6	1
Boeing	5789	0	2026	2038	Atlas V	10	125	Xenon	7	2
Astra	13620	0	2022	2032	Falcon 9	23	50	Xenon	7	2
Mangata networks	791	0	2024	2034	Falcon 9	23	500	Xenon	7	2
Amazon Kuiper	7774	0	2022	2029 (3246 sats) 2032 (7774 sats)	Atlas V (6%) Vulcan Centaur 6 (19%) Ariane 64 (13%) New Glenn (61%)	10 27 22 45	700	Xenon	7	2
GalaxySpace	999	1	2022	2032	Long March 2C	4	190	Xenon	7	2

Constellations: results



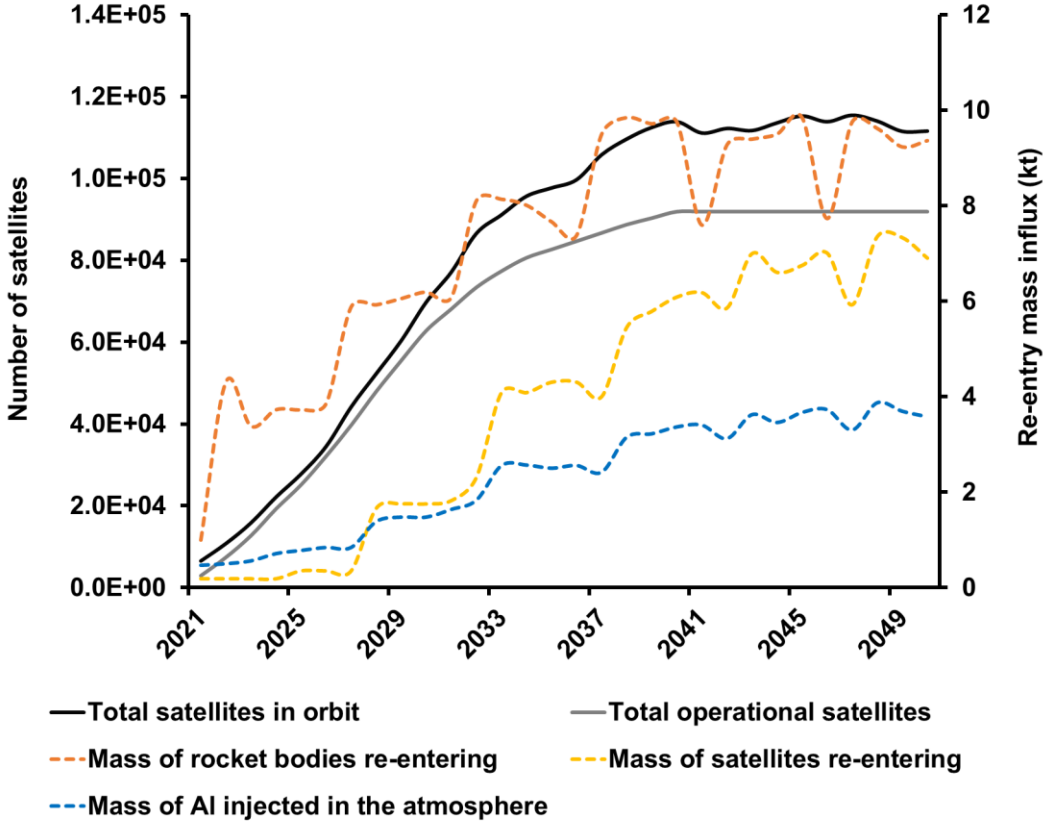
Earth

Evolution of launches and of environmental impacts w.r.t. baseline activities



Space

Evolution of the number of satellites in orbit and mass of artificial objects re-entering



<u>Satellites</u>

112,000 in orbit in 2050

15,000/yr placed in orbit after 2040

<u>Re-entries (after 2040)</u>

16kt objects/yr

3.5kt aluminium/yr (x27 natural level)

Other activities: modeling

SPACE TOURISM

Suborbital


Companies: Virgin Galactic and Blue Origin
Scenarios: **3** to 11 daily launches per company by 2050

Orbital

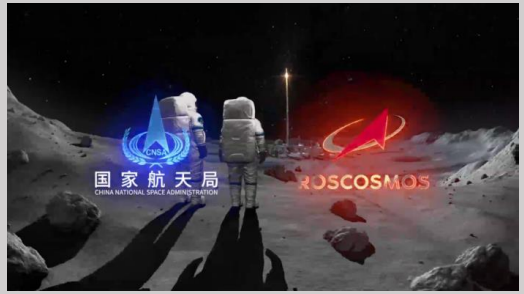

Company: SpaceX
Scenarios: **2** to 8 monthly launch (50-50% Falcon 9 / Starship)

MOON MISSIONS

Artemis

NASA
Commercial Lunar Payload Services
Lunar Gateway Program

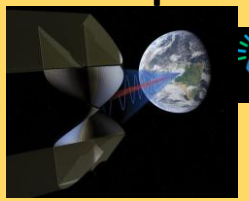
International Lunar Research Station



Other missions

SBSP

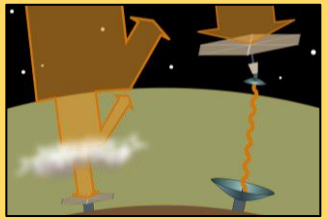
UK Space Energy Initiative



Space Energy Initiative

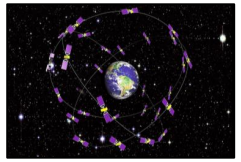
25x2GW by 2050
569 Starship launches

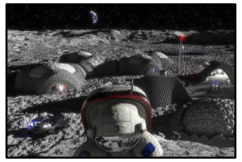
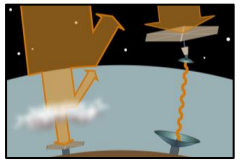
China SBSP plan



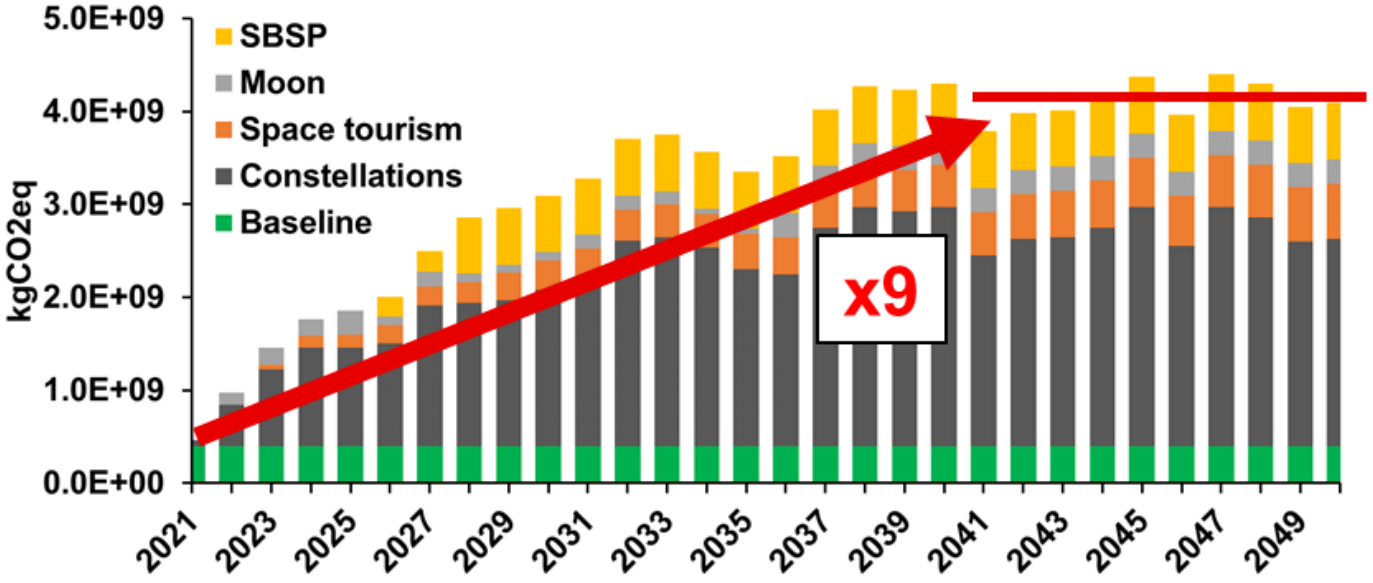
1GW by 2050
100 LM9 launches

Other activities: results

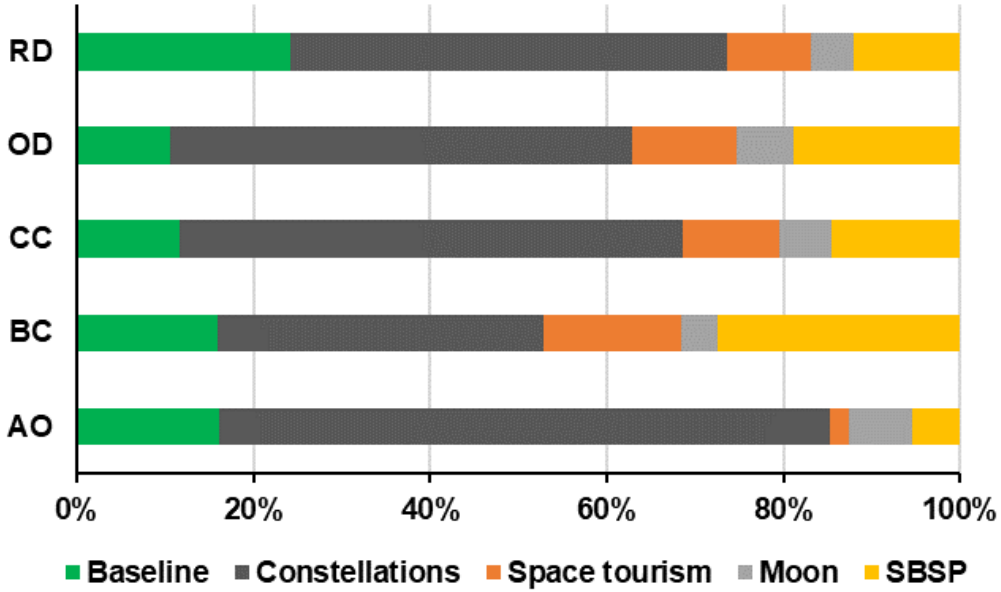



Evolution of the impacts on climate change



Activities responsibilities in cumulative 2021-2050 impacts



By the 2030s

Al2O3 x6.5

BC x7.3

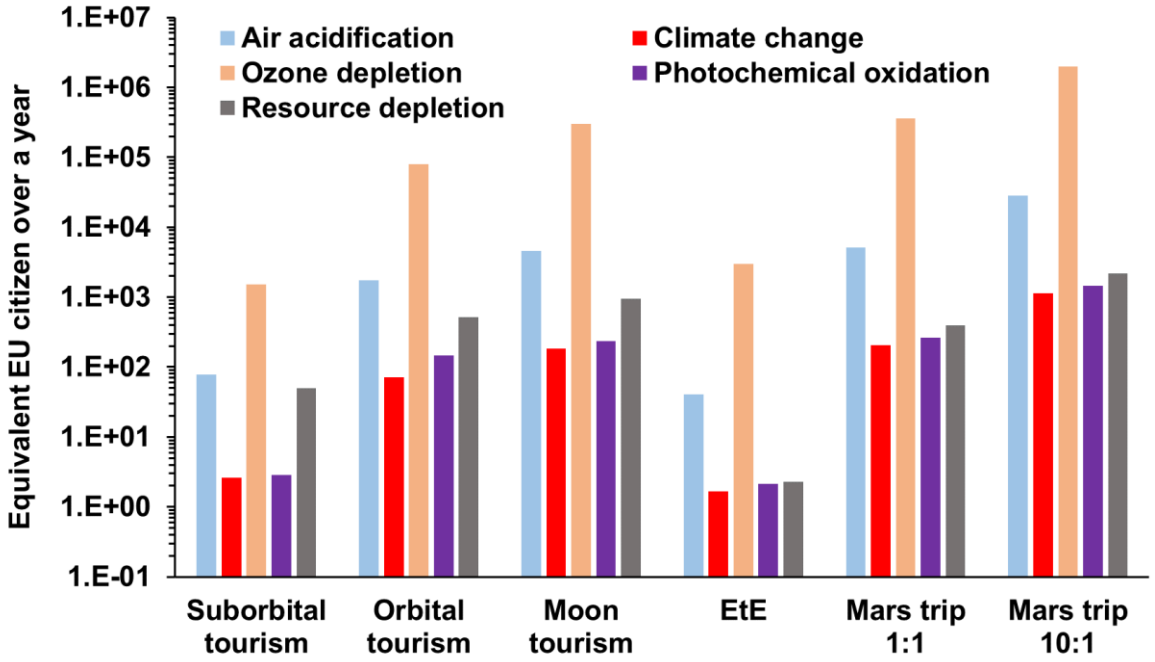
Highly dependent on launchers used

→ **≈ Global aviation radiative forcing of 2019**
+ concerning ozone depletion levels
(based on Ross et al. & Ryan et al. findings)

Space tourism and environmental justice

Environmental footprints of passengers in typical space travel flights

No or simplified account of high-altitude effects of launch emissions



Equivalent EU-27 citizen **over 1 year**

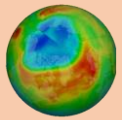
	SUBORBITAL FLIGHT	ORBITAL FLIGHT	AROUND-THE-MOON FLIGHT	EARTH-TO-EARTH FLIGHT
CLIMATE CHANGE (WITHOUT HIGH-ALTITUDE EFFECTS)	3 (24 tCO2eq)	70 (660 tCO2eq)	180 (1700 tCO2eq)	1.7 (15 tCO2eq)
OZONE DEPLETION (WITH PROXY HIGH-ALTITUDE EFFECTS)	1 500	80 000	300 000	3 000
TICKET PRICE	450k$ - 28M$	55M$	?	1k$
WORLD'S WEALTHIEST %	0.0025%-0.0001%	0.0001%	<0.0001%	-

Environmental impacts of the planned space tourism industry*

accounting for high-altitude effects of launch emissions (Ryan et al., 2022)

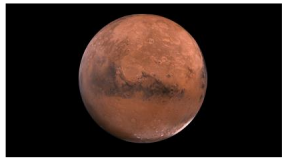
*daily suborbital flights + weekly orbital flights

≈1/10th of global aviation radiative forcing after 3 years



Arctic ozone decline undermining progress made by the Montreal Protocol after 10 years

Speculative activities: modeling



EARTH-TO-EARTH TRANSPORTATION

Starship, 1,000 passengers / flight

Method 1: 25% of supersonic aviation market

Method 2: 25% of long-haul aviation market (>10h)

Very high reuse rates

MARS COLONISATION

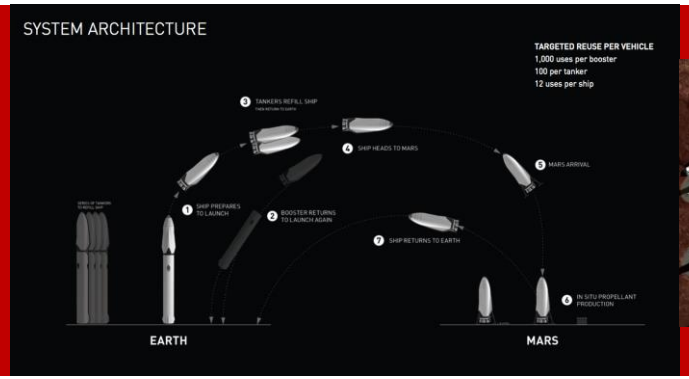
Mars vehicle, 100 passengers / flight, 100t cargo

Cargo-to-person ratio 1:1 and 10:1

5 refueling with tankers

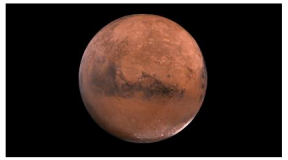
100k and 1M people by 2050

Very high reuse rates



Speculative activities: results

AGI = Annual Global Impact (2010)
PB = Planetary Boundary



Earth-to-Earth transportation

Year 2050

	25% SUPERSONIC AVIATION		25% LONG-HAUL AVIATION	
LAUNCHES/DAY	16		103	
CITIES CONNECTED DAILY	4		10	
	AGI	PB	AGI	PB
AIR ACIDIFICATION	3.0%	1.1%	18.7%	7.2%
CLIMATE CHANGE	0.2%	1.3%	1.0%	8.4%
OZONE DEPLETION	227.0%	70.9%	1437.5%	449.0%
BLACK CARBON EMISSIONS / BASELINE	**x140**		**x860**	

Mars colonisation

Typical launch window year

	CARGO-TO-PERSON 1:1		CARGO-TO-PERSON 10:1	
LAUNCHES/DAY	33		181	
	AGI	PB	AGI	PB
AIR ACIDIFICATION	6.2%	2.4%	33.8%	13.0%
CLIMATE CHANGE	0.3%	2.6%	1.7%	14.3%
OZONE DEPLETION	460.0%	143.7%	2530.0%	790.1%
BLACK CARBON EMISSIONS / BASELINE	**x290**		**x1580**	

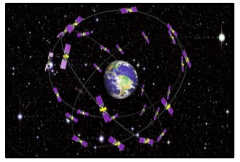
Mitigation?

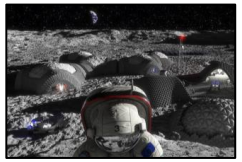
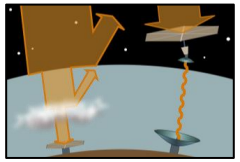
→ **Low carbon LOx & methane** production does not act on **BC emissions and other high-altitude effects**
→ **Low carbon LH2** does not act on **other high-altitude effects**
→ Such **high demands** in low carbon fuels would **enter in conflict with global decarbonization efforts**

Conclusion and implications

Planned large space projects would (constellations, tourism, Moon missions, SBSP)

- Make the impacts of the space sector on Earth significant, mainly due to high-altitude effects
- Exacerbate environmental inequalities (tourism)
- Threaten astronomical observation (light pollution - constellations)
- Undermine the sustainability of the space environment (space debris - constellations)



Speculative projects would (Earth-to-Earth, Mars colonisation)

- Have prohibitive impacts on the Earth's environment
- Lead to very high energy and materials demand in a context of growing scarcity and turmoil


Environmental sustainability stands as a major constraint to intense space activities

- Large scale space resource use for consumption on Earth (minerals, energy,…) → Ex: assessments of SBSP potential benefits must investigate high-altitude effects
- Democratized space tourism
- Put polluting industries in space
- Making humanity a multiplanetary species
- …

Findings point towards a different narrative of the future of humanity in space

Contribution

Evaluation of the environmental impacts of future proposed space projects over the period 2021-2050 through a streamlined LCA

- Review and synthesis of plans proposed by actors of the space sector for the future
- Evaluation of the impacts of different types of space activities, many of which for the first time
- Assessment based on real plans and systems
- Use of best available estimates and highlighting of critical knowledge gaps
- Findings analyzed in the context of global ecological situation to provide a systemic view


Acta Astronautica

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Space Safety & Sustainability Project Group

Q&A

Emissions indices and characterisation factors

Emissions indices [g/kg of propellant]

	N2	CO2	CO	H2O	H2	ClOx	HOx	NOx	HCl	Al2O3	BC
METHALOX	0.0	378.2	164.3	449.3	0.0	16.0	3.0	1.0	0.0	0.0	0.8
KEROLOX	0.0	451.2	254.7	287.8	60.0	16.0	3.0	1.0	0.0	50.0	20.0
HYDROLOX	0.0	0.0	0.0	992.0	248.0	16.0	3.0	1.0	0.0	0.0	0.0
AP AL/HTPB	80.0	108.0	16.2	384.0	96.0	80.0	15.0	5.0	150.0	330.0	0.0

x25

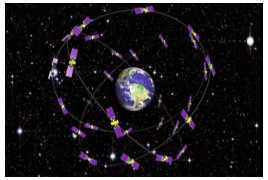
Characterisation factors

	N2	CO2	CO	H2O	H2	ClOx	HOx	NOx	HCl	Al2O3	BC
AIR ACIDIFICATION [kg SO2eq]	0	0	0	0	0	0	0	0.7	0.88	0	0
CLIMATE CHANGE [kg CO2eq]	0	1	1.57	0.06	0	0	0	114	0	0	0 (reference) 1166 (sensitivity)
OZONE DEPLETION [kg CFC-11eq]	0	0	0	0	0	0.7	0.7	0.7	0.7	0	0

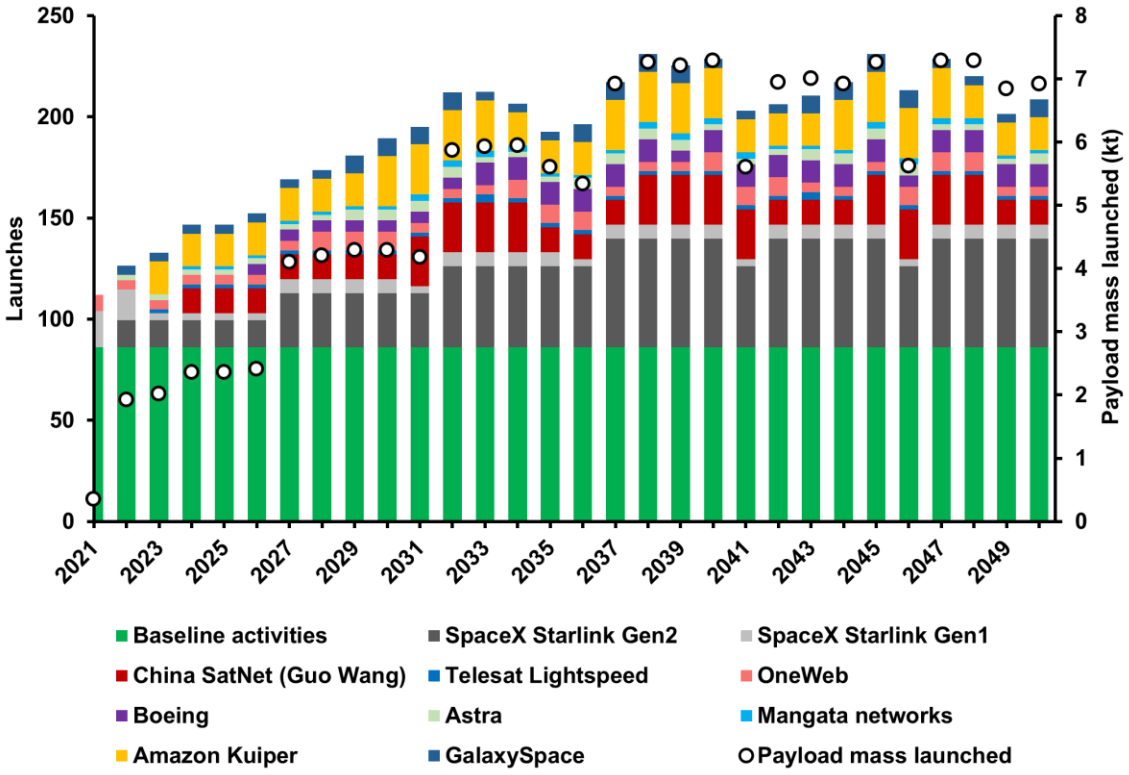
Limitations

Incompleteness of proposed plans and lack of data availability, leading to various assumptions to model space activities ➔ not full representativity
Limited scope ➔ underestimates
No technological progress
Highly simplified modeling of the impacts of launches

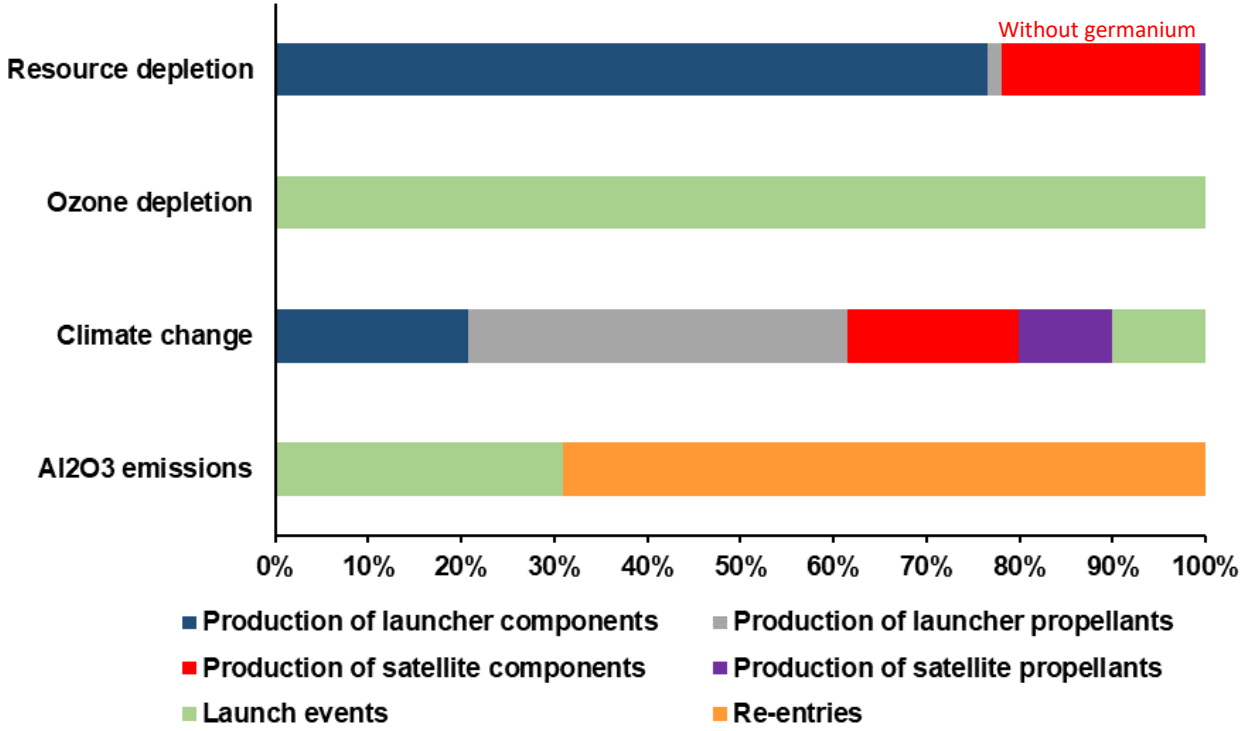
Constellations: results



Evolution of the number of launches and payload mass launched of baseline and constellation activities



Source of impacts over 2021-2050 period



Sensitivity analysis: BC and re-entry NOx

Increase in LCIA results

	IMPACT CATEGORY	LOW GROWTH SCENARIO	MODERATE GROWTH SCENARIO	HIGH GROWTH SCENARIO
RE-ENTRY NOx	Air acidification	6%	22%	23%
	Climate change	5%	15%	15%
	Ozone depletion	12%	22%	22%
BLACK CARBON	Climate change	36%	29%	28%

Mitigation of the impacts of speculative plans?

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).

	BIOMETHANE			LOW CARBON H2 (ELECTROLYSIS + CCUS)		
	MASS REQUIRED (MT)	IEA SPS	IEA SDS	MASS REQUIRED (MT)	IEA APS	IEA NZE
SSA-25	5.9	8% (23%)*	3% (13%)	2.7	3% (14%)	1% (5%)
LHA	37.5	50% (143%)	18% (84%)	17.2	17% (86%)	5% (34%)
MARS LAUNCH WINDOW 100K	2.9	4% (11%)	1% (6%)	1.3	1% (7%)	0% (3%)
MARS LAUNCH WINDOW 1M	28.8	38% (110%)	14% (64%)	13.2	13% (66%)	4% (26%)

*Numbers in parenthesis indicate the share of the demand in the transport sector.