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Environmental life cycle assessment of reusable launch vehicle fleets: Large climate impact driven by rocket exhaust emissions

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ABSTRACT

After the success of the reusable Falcon 9 rocket, space actors are pursuing competitive space access by developing Reusable Launch Vehicles (RLVs). While this initiative may enhance recycling rates, it may also trigger the Jevons' paradox as it amplifies the overall environmental footprint due to increased launch frequencies. It is therefore essential to quantify RLVs' impacts and identify key design drivers to enable efficient design choices while mitigating undesirable environmental effects.

Consequently, this article uses a space specific Life Cycle assessment (LCA) approach to evaluate the environmental footprint, in terms of climate impact, water depletion and land use, of different RLV fleets designed to serve a forecasted European space market. The results show that the LH_2 fleet options have 2–8 times lower carbon footprint when compared to the LCH_4 fleet as a result of lower propellant consumption and lack of black carbon emissions, suggesting that the environmental burdens are mostly driven by propellant choice. Moreover, the analysis reveals a potential underestimation of climate impacts in previous LCA's by 2–3 orders of magnitude due to the absence of high altitude characterisation of rocket exhaust emissions and demised aluminium oxides. This increased forcing could lead to fleet choices surpassing the Earth's carrying capacity given by its planetary boundaries.

The methodology and results within this study can support further integration of launch and reentry emissions within LCA by refining modelling techniques, improving impact characterisation and quantifying uncertainties. These advancements can ultimately enable robust eco-design strategies for launch vehicles.

1. Introduction

Reusable launch vehicles (RLVs) are establishing themselves as the most competitive option to support the expected growth of the space market [1]. As a consequence, the main commercial launch vehicle providers are currently rushing to develop the next generation of RLVs, primarily fuelled by methane (CH_4), and based on vertical take-off vertical landing (VTVL) launch vehicles with Down Range Landing (DRL) and return to launch site (RTLS) capabilities.

However, as launch rates exponentially increase, the limits of our planet are also becoming increasingly apparent, in the form of resource scarcity, biodiversity loss and climate change. Within this context, space presents an adaptation-mitigation dilemma; while certain space activities, as Earth observation, can help humanity understand and monitor its environmental footprint, the launch vehicles sustaining the whole space economy emit material directly into every layer of the atmosphere, causing significant warming and depleting stratospheric ozone [2–4]. Moreover, this atmospheric burden might further escalate in the forthcoming years due to two primary factors. Firstly, as reusability of launch vehicles is introduced, the consequential reduction in payload performance can lead to a burden shift from material scarcity to atmospheric impacts [5]. Secondly, reusability is also leading to reduced space access costs, which are translating in an exponential increase in launch frequencies and proposed space activities, including space tourism [6]. In this way, RLVs may turn out to be a prime example of the rebound effect associated with the Jevons' paradox [7], with resource efficiency leading to larger absolute emissions. The increase in launch rates and emissions, combined with anticipated exacerbation of the environmental crisis over the coming years, may lead to an inflexion point in public awareness about the potential environmental costs of the spaceflight industry, forcibly steering policy and regulations

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Acronyms

3STO	Three Stages To Orbit
BC	Black Carbon
CF	characterisation Factor
DLR	German Aerospace Center
DRL	Down Range Landing
ELV	Expendable Launch Vehicle
GG	Gas-Generator engine cycle
GTP	Global Temperature Change Potential
GWP	Global Warming Potential
IAC	In Air Capturing
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LOP	Agricultural Land Occupation
RLV	Reusable Launch Vehicle
RTLS	Return To Launch Site
SC	Staged Combustion engine cycle
SLME	Space Liner Main Engine
SSSD	Strathclyde Space Systems Database
TSTO	Two Stages To Orbit
VTHL	Vertical Take-off Horizontal Landing
VTVL	Vertical Take-off Vertical Landing

in the sector [8]. As such, there is added importance for space agencies, companies and other stakeholders to be able to scientifically quantify the environmental impacts of launchers and design them to ensure a certain extent of mitigation through eco-design practices.

The atmospheric impact of launchers include the direct alteration of stratospheric ozone concentration [9–12], the creation of large polar mesospheric clouds [12] and the injection of climate-altering long-living greenhouse gasses and aerosol pollutants in the upper atmosphere [2–4,13,14]. However, previous launcher Life Cycle Assessments (LCAs) [15,16] have only considered the effects of CO_2 and CO emissions using ground-based climate metrics, failing to take into account the effects of H_2O, NO_x and key aerosols in the upper atmosphere layers leading to an erroneous conclusion that the climate footprint of the launch event is negligible.

Given that impacts are mostly driven by emissions to the upper atmosphere, it appears that mission performance and propulsion design choices have the largest influence on the environmental footprint of a launch vehicle. Specific emissions of concern such as black carbon (BC) are mostly driven by hydrocarbon fuels, engine cycles, film cooling and oxidiser to fuel (O/F) ratios, which are highly integrated with other system design choices. It is therefore necessary to fully quantify the environmental sustainability of different launch architectures [5,6].

There has been previous studies assessing the impacts of different design choices. Romaniw et al. [17] examined the environmental impact of light weighting structural components of Expendable Launch Vehicles (ELVs) finding that these are generally translated to reduced life cycle impacts. Neumann [18] assessed differences in environmental impacts between existing ELVs and RLVs. Nevertheless, the methodologies did not account for impacts of non-CO_2 emissions in the upper atmospheric layers. Other studies did account for these in comparisons between different launch vehicles. A previous study by Ross et al. [2] addressed the influence of propellant choice on the atmospheric radiative forcing with climate simulations, but the functional unit was not entirely representative of launch vehicles as it assumed similar propellant masses for all options. The issue was partly addressed recently with an LCA framework [5] which included the use of proxy launch vehicles designed for a common payload mass to orbit with a simplified optimal staging methodology [19]. Nevertheless, the sizing methodology was highly simplified, the characterisation of emissions did not account for stratospheric radiative forcing and the chosen functional unit may not fully address the suitability to compete in forecasted launch market scenarios.

Within this study, different reusable launch vehicles fleets were assessed using an LCA framework including high altitude effects. The fleets were designed to serve the same set of missions and are composed of launchers with two stages to orbit (TSTO) with and without reusable boosters, three stages to orbit (3STO), different propellant types as LH_2 and CH_4, and VTVL with DRL recovery or winged VTHL with IAC recover options. The launch vehicle families and their composition are summarised in Section 2. Section 3 presents the Strathclyde Space Systems Database [20] and an updated LCA methodology for launch vehicles based on Ref. [5] and Ref. [6]. Section 4 assesses the environmental life cycle impact and includes a sensitivity assessment on the fleet reusability and in the climate characterisation factors (CFs). This study is then concluded in Section 5 including recommendation for future work on environmental assessments and eco-design of launchers.

2. Launch vehicle fleets assessed

This study assessed three launch vehicle fleets, which were each composed of multiple launch vehicle types sharing some commonalities. Each fleet was tailored to accommodate the same forecasted European launch market [1] thanks to their flexibility to be integrated in different launch vehicle architectures with two or more stages and boosters. The forecasted market is composed of a set of missions delivering payloads to multiple orbits, which is the functional unit for the LCA. These are analysed in larger technical detail in Refs. [1,21,22], with their technical data shown in Table 1, including the average number of launchers of each type per fleet. The respective launcher layouts are shown in Fig. 1 with their composition being summarised below:

- Ballistic vertical take off and vertical landing (VTVL) fleets with the hydrogen fuelled Prometheus-H gas-generator (GG) as engine or the methane fuelled Prometheus-M GG. These are tailored for DRL manoeuvres, landing on a floating barge and being towed back by a tugboat. This family was composed of TSTO vehicles with expendable upper stages. An XXL option used side boosters with a common core which may be reusable depending on the mission. The reusable first stage and boosters were assumed to achieve around 15 reuses before expended. This may be seen as equivalent to SpaceX's Falcon 9 and Falcon Heavy fleet technology.
- Winged vertical take off and horizontal landing (VTHL) with hydrogen as fuel using the Space Liner main engine (SLME) with a staged combustion (SC) engine cycle [23], and performing an in-air Capturing (IAC) recovery manoeuvre with an aircraft (for DRL), as studied by DLR [24]. This launch vehicle family would use a small expendable upper stage using the Vinci engine, a larger upper stage using a vacuum adapted SLME, or the two combined within a 3STO tandem configuration. The reusable first stage was assumed to achieve 50 reuses before expended, a larger number than for the VTVL vehicles as a consequence of the possibly smoother flights with lower aero-thermal peak loads, resulting in reduced maintenance effort. This fleet showed the highest performance in terms of total take off mass, despite a 4% larger total dry mass when compared to the VTVL LH_2 configuration.

3. Life cycle assessment methodology

This section describes the LCA methodology used in this study starting with a description of the space specific database used, outlined in Section 3.1, and followed by Sections 3.2 to 3.6 which describe the specific foreground processes used to assess the launch vehicle fleets.

Table 1
Reusable launchers analysed. The corresponding fleet sketches can be seen in Fig. 1. The last row reports the average number of total launches necessary for a robust cost optimal fleet lifting the same payload [1]. Cores and boosters are represented with a (c.) and (b.), respectively. Each mass represents values for each block. From Sippel et al [21].

Fleet		LH_2 VTVL L&XXL			LCH_4 VTVL L&XXL			RLVC4 VTHL		
Launcher Name		L-RLV: H240 + H61	XXL-RLV: 2 H240 + H240 + H61	XXL-RLV, exp. core.: 2 H240 + H240 + H61	L-RLV: M520 + M110	XXL-RLV: 2 M520 + M520 + M110	XXL-RLV, exp. core.: 2 M520 + M520 + M110	RLVC4 VTHL Mini-TSTO	RLVC4 VTHL TSTO	RLVC4 VTHL 3STO
Propellant		LOX/LH_2			LOX/LCH_4			LOX/LH_2		
Stage 1/Boosters	m_d [Mg]	25.675			30.435			64.4		
	m_p [Mg]	240			520			378.2		
	O/F [-]	6.0			2.67			6.5		
	n_r [-]	15			15			50		
	Rec.	DRL			DRL			IAC		
	d_{drl} [km]	740	1511 (c.) 1160 (b.)	Exp. (c.) 1160 (b.)	650	1470 (c.) 974 (b.)	Exp. (c.) 974 (b.)	2650	630	630
Engines	Type	4 x Prometheus-H GG			7 x Prometheus-M GG			4 x SLME		
	m_e [kg]	1551			1288			3096		
Stage 2	m_d [Mg]	6.068			6.299			3.3	13	
	m_p [Mg]	61			110			14	150	
	O/F [-]	6.0			2.8			5.8	5.5	
Engines	Type	Vac. Prometheus-H GG			Vac. Prometheus-M GG			Vinci	Vac. SLME	
	m_e [kg]	2352			1792			816	3375	3375
Stage 3	m_d [Mg]									3.3
	m_p [Mg]									14
	O/F [-]									5.8
Engines	Type									Vinci
	m_e [kg]									816
Fairing	m_d [kg]	1625	2500	2500	1625	2500	2500	1650	3000	3000
Launches	n [-]	55.4	145.1	43.7	65.1	121.5	66.6	40.2	137.5	68.1

3.1. Space-specific life cycle inventory (LCI)

An updated version of the Strathclyde Space Systems Database (SSSD) v1.0.3 using the latest Ecoinvent version (3.9.1) as the only background inventory was used to solve the inventory database of each launcher configuration. The SSSD is a space-specific Life Cycle Sustainability Assessment (LCSA) database which can be used to determine the environmental impacts of a space system. The SSSD was developed in openLCA using a process-based, attributional methodology which relies on physical activity data to create a product tree. Validated at ESA through a collaborative project in late 2018, the SSSD consists of space-specific life cycle sustainability datasets, based on Ecoinvent and ELCD background inventories, which each contain environmental, costing and social data. Additionally, the SSSD aligns closely with a variety of widely accepted international standards and norms. Further information on the development of the SSSD is outlined by Wilson [20]. A diagram outlying how space specific databases interact with dedicated foreground activities and generic background inventories representing the rest of the technosphere can be seen in Fig. 2.

The database was extracted in python, decoupling space specific processes from background databases and enabling non-linear modelling of the background inventory database and faster computation. It will eventually provide drivers to alternative background inventories such as Gabi or the open-source ELCD database, addressing their differences and uncertainties [25]. The LCA problem for launchers was then constructed as shown in Fig. 3 and then solved with a Brightway2 driver to evaluate the background Ecoinvent inventory and perform the impact assessment with modified LCIA methods. The tool composed of only the space specific background and foreground processes can be accessed on request.[1]

3.2. Life cycle impact assessment (LCIA)

The analysis used five midpoint impact categories, one for water use based on the AWARE LCIA [35] implemented in OpenLCA, one for land use based on ReCiPe 2016 v1.03, midpoint (E) agricultural land occupation (LOP) [36] and three for climate change. These were global warming potential over 100-year time horizon (GWP100), global warming potential over 20-year time horizon (GWP20), and Global Temperature change Potential over 100-year time horizon (GTP100). GWP and GTP are different methods for comparing the relative impact

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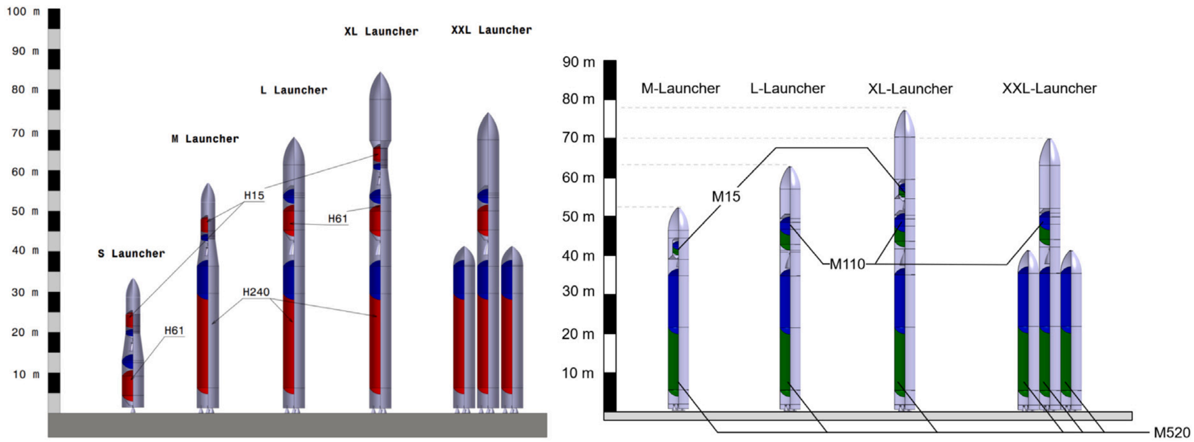
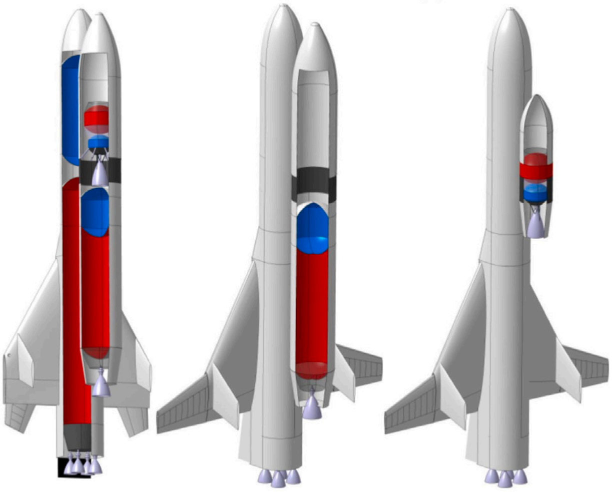
[1] Private repository is available on requests through https://github.com/strath-ace-labs.



(a) LH2 VTVL launchers family (b) LCH4 VTVL launchers family



(c) RLV-C4 VTHL launchers family

Fig. 1. Sketches of the different fleets analysed in this study. From Sippel et al. [21]. Only the vehicles corresponding to the cost optimal fleet compositions derived by [1] were analysed.

Table 2
Climate change life cycle impact per kg of emission. Values from IPCC [26] for ground based emissions unless otherwise stated, Lee et al [27] for aviation cruise emissions, and derived using the GWP methodology from radiative forcing as described in an accompanying publication [28] and by Miraux et al [29] for high altitude emissions.

Species	GWP_{100}			GWP_{20}			GTP_{100}		Reference
	Aviation	Ground	High altitude	Aviation	Ground	High altitude	Aviation	Ground	
H_2O	6×10^{-2}	5×10^{-4}	1.48×10^3	0.22	-1×10^{-3}	5.18×10^3	0.008	0.	[30]
NO_x	114	8.5		619	31.5		13	−0.65	[31,32]
H_2	12.8	12.8		40.1	40.1		2.3	2.3	[33]
CH_4	29.8	29.8		82.5	82.5		7.5	7.5	
CO	4.0	4.0		9.2	9.2		1.95	1.95	
CO_2	1.00	1.00	1.31	1.00	1.00	3.29	1.00	1.00	
BC	1166	900	1.60×10^6	4288	3200	5.59×10^6	161	130	[34]
Al_2O_3			2.79×10^5			9.78×10^5			

of a climate forcing agent with respect to carbon dioxide. The first one is the integral of radiative forcing change response at the top of the atmosphere for a pulse emission, and the second one is the average temperature change at the surface. These are highly dependent on the time horizon, location of the emission, associated lifetime, meteorological conditions, and other factors [37].

As a first approximation, since no GWP and GTP factors were available for launch and reentry emissions, CFs of kg CO_2eq for aviation [27] were assumed as the most analogous, as has been done in previous studies [5,6]. However, it should be noted that recent studies from The Aerospace Corporation [2] have estimated a significant contribution from the emission at high altitudes as a consequence of different chemical reactions, higher residence times and the relatively decoupled atmospheric layers. These could also lead to increased cloudiness which may have additional environmental impacts [11,12] comparable to aviation cirrus clouds.

To attempt to quantify the potential uncertainty ranges, a sensitivity analysis was included in this study with ground releases based CFs reported by the IPCC [26] and assumed in previous space industry LCA studies [15,38], and CFs for high altitude emissions derived from past studies as described in Section 4.4. Table 2 summarises the values

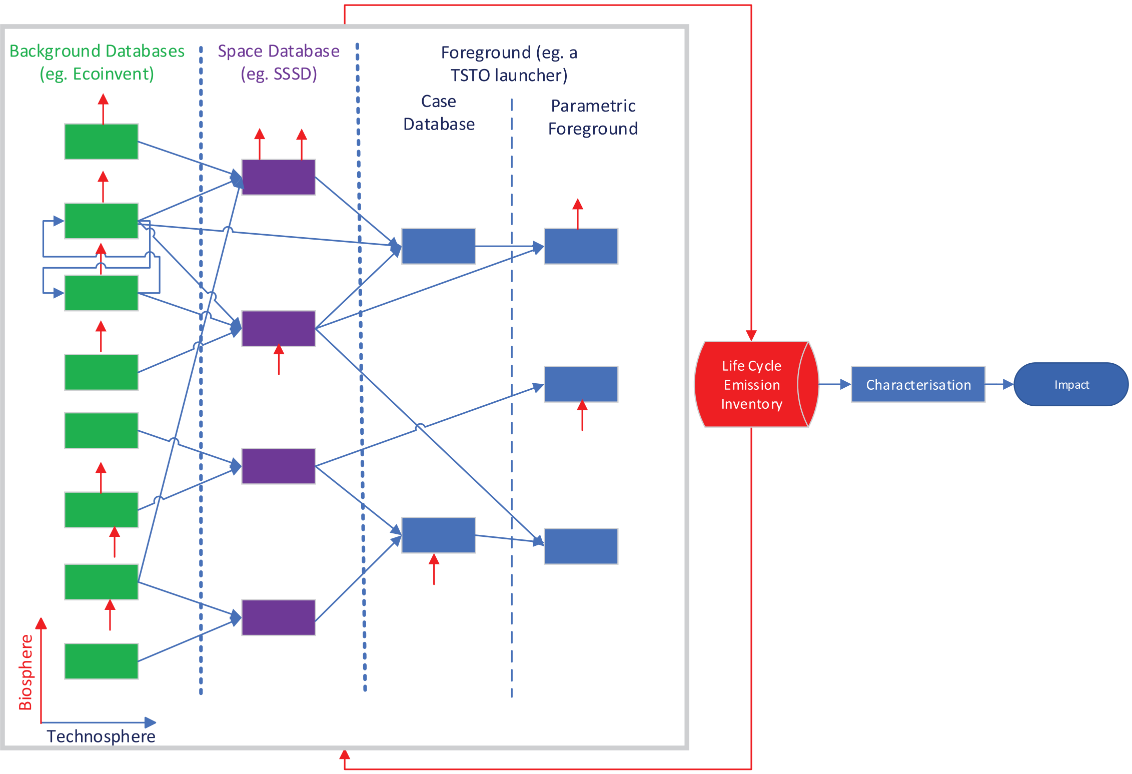


Fig. 2. Generalised space based LCA processes.

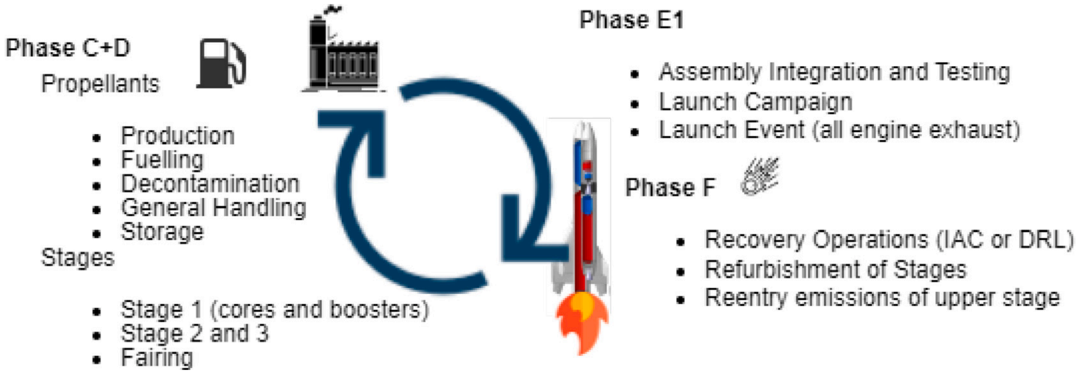


Fig. 3. Space LCA phases and processes included within the system boundaries.

Table 3
Climate change life cycle impact for a kg of propellant represented in carbon dioxide equivalents ($CO_{2,eq.}$). The change in the impact when including the characterisation of the H_2, NO_x and H_2O emissions from background processes is shown in the % CFs. columns.

Propellant	Type	GWP_{100}		GWP_{20}		GTP_{100}	
		[$CO_{2,eq.}$]	[% CFs.]	[$CO_{2,eq.}$]	[% CFs.]	[$CO_{2,eq.}$]	[% CFs.]
LH_2	Cradle to loading	17.9	2.6%	22.2	7.9%	16.1	0.0%
	Production	9.9	1.4%	12.2	4.5%	8.9	−0.1%
LCH_4	Cradle to loading	10.8	2.1%	13.6	6.6%	9.7	−0.2%
	Production	3.6	1.5%	4.2	4.9%	3.3	−0.1%
LO_x	Cradle to loading	8.1	2.4%	9.9	7.8%	7.3	−0.2%
	Production	1.2	1.7%	1.4	5.5%	1.1	−0.1%

assumed for the extended LCIA method both for the ground, aviation, and high altitude CFs.

3.3. Propellants

The life cycle impacts of the different propellants used for this study are shown in Table 3, including all propellant related activities and the relative increase (% CFs.) when accounting for the CFs from Table 2 in the background processes. It can be seen that the life cycle from cradle to loading of hydrogen rocket fuel, mostly consisting of the energy intensive production through natural gas steam reforming, has a considerably higher impact than methane rocket fuel. It is also seen how the characterisation of hydrogen emissions in background processes leads to an increase in the cradle to loading impact which is

Table 4
Main emission indexes in g/kg of burned propellant for the different engines considered in this study.

Exhaust	Prometheus-H	Prometheus-M	SLME
BC		4.6916	
CH_4		54.706	
CO_2		312.4	
CO		168.8	
H_2	47.706	5.4457	24.133
H_2O	928.4	425.6	975.8
OH_x	19.160	17.816	0.018
NO_x	1.0	1.0	1.0

especially noticeable in GWP20. In addition to the activities mentioned above, a leakage rate of 1% of the total fuel for the space specific activities was assumed, although this might be an underestimation given hydrogen and methane fugitive emissions [39,40] and the large venting operations observed during propellant loadings. These rate may also be higher for hydrogen, as a consequence of its reduced molecular mass and stricter storage and handling conditions. It should be noted that the life cycle impacts may change significantly in the future, specially with the use of sustainable fuels as green hydrogen or biomethane. For example, a prospective LCA recently estimated that green liquid hydrogen produced through wind energy could achieve up to an order of magnitude lower carbon footprint [41]. Nevertheless, it could also produce a burden shift towards other impact categories, such as mineral resource depletion [41].

3.4. Production and refurbishment

For production, it has been assumed that there are no differences between the vehicles types due to a lack of inventory data. The inventory was predominately based on a literature review reported in Refs. [18, 20], with some data extrapolation for the manufacturing processes. Generic aluminium processes were used rather than aluminium alloys. Refurbishment operations were mainly based on the space shuttle orbiter and sized per kg., although this might overestimate its impacts given that the shuttle required heavy refurbishment operations after spending several days in orbit and recent reductions in operational effort from new launch providers.

3.5. Recovery operations

The impacts during stage transportation activities in the recovery operations include direct emissions from a tug boat and supply vessel for the VTVL case, and from an aircraft for the VTHL case. Values for fuel consumption were scaled based on a per km basis from a recent study on cost estimations for recovery operations of similar RLV stages [42,43]. Typical global averaged emission indexes and GWP were then applied to the vessels and aircraft [27]. Sulphur oxides (SO_x) emissions from shipping were excluded given the current state of uncertainty in its indirect GWP values [44], unknown proxy ships, and because of current worldwide efforts to reduce maritime SO_x emissions in the short term due its harmful effects on humans and the ecosystem [45]. Their indirect emissions from their corresponding production, retro-fittings, refurbishment and other upstream activities were added through a proxy estimation and assumed to be amortised over 150 launches.

3.6. Launch and reentry emissions

Emissions from launch vehicles are a result of combustion exhaust compounds and subsequent plume reactions, nozzle film cooling emissions, material releases at high altitudes during high speed demisable reentries [46,47] and from high temperature chemical reactions occurring within induced hypersonic shock-waves [11,48]. Within this study, the direct nozzle exit emission indexes (EI) were obtained from RPA and are shown in Table 4, except for NO_x which was assumed based on the SSSD [38]. The RPA calculation assumptions are chemical equilibrium up to low supersonic expansion and “frozen composition” afterwards, and only includes those above a default threshold. For BC, it was assumed that the turbine flow had an EI of 64.4 g/kg, and that this would mix with the nozzle flow. Plume post-combustion phenomena was also modelled by analysing RTLS trajectories from Falcon 9 and employing an empirical model previously used in Ref. [49] derived from infrared plume measurements [50,51]. This estimated that although only 58.9% of all propellant was burned in the stratosphere, nearly all BC was released above the troposphere. Specifically, it was assumed that 75.4% of the BC emitted in the stratosphere was unburned, as opposed to the post-combustion of 96% of the BC emitted within the troposphere. For reentry emissions, only alumina and nitrogen oxide emissions for the demised upper stages was included. Reentry emissions from reusable first stages was neglected as they typically enter at lower speeds, gaining kinetic energy at lower atmospheric altitudes than the space shuttle. At those aerothermodynamic regimes, vibrations excitation and dissociation onset is delayed by higher pressures [52]. Nevertheless, given the geometry and flight profile dependency and possible high entry kinetic energies for reusable first stages with higher staging conditions, this perfect gas assumption should be revised in the future.

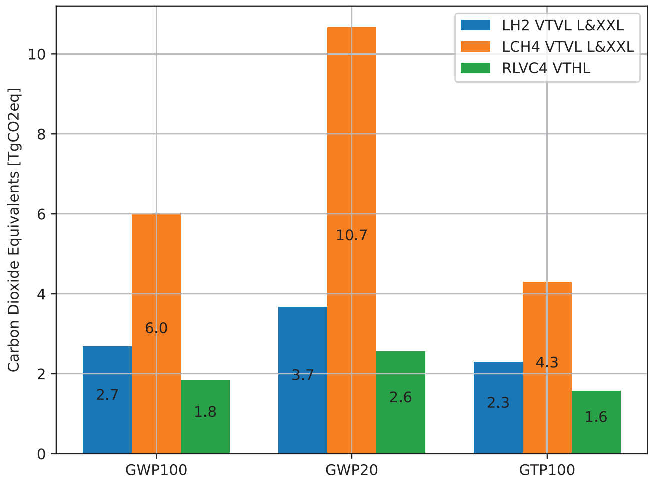


Fig. 4. Fleet total climate change life cycle impacts assessed with the extended impact assessment methods.

4. Environmental impacts of RLVs

The launch vehicles described in Section 2 were then assessed with the LCA framework discussed in Section 3. Results are presented in Section 4.1, followed by a contribution analysis of the life cycle impacts in the sensitivity assessment in Section 4.2, a sensitivity assessment on the reuse rates in Section 4.3, and a sensitivity assessment of the CFs assumed in Section 4.4.

4.1. Fleet assessment

Table 5 shows the environmental impacts per launch and the increase with respect to assumed fully ground based emissions for the launch vehicles shown in Fig. 1 based on their technical data from Table 1. The aggregate impact for each fleet can be seen in Table 6 and Fig. 4.

The results show that the RLVC4 fleet achieved the best performance in all impact categories, followed by the VTVL LH_2 fleet with a 46% higher GWP100, and approximately 32% increased water and

Table 5
Life cycle impacts per launch from the different launch vehicles types assessed with the extended impact assessment methods using the aviation CFs from Table 2 and represented in carbon dioxide equivalents ($CO_{2,eq.}$). The percentage shows the increase with respect to ground based CFs for climate change.

Launcher	GWP_{100}		GWP_{20}		GTP_{100}		Water	Land
	[$CO_{2,eq.}$]	[% G.]	[$CO_{2,eq.}$]	[% G.]	[$CO_{2,eq.}$]	[% G.]	[Mm^3]	[ha]
L-RLV: H240 + H61	4.71	0.5%	6.44	2.0%	4.01	0.1%	6.3	9.7
XXL-RLV: 2 H240 + H240 + H61	12.49	0.5%	17.20	1.9%	10.61	0.1%	15.0	26.3
XXL-RLV, exp. core.: 2 H240 + H240 + H61	13.99	0.5%	18.75	1.8%	12.08	0.1%	16.7	29.2
L-RLV: M520 + M110	10.36	3.6%	18.51	8.9%	7.35	0.6%	11.2	17.9
XXL-RLV: 2 M520 + M520 + M110	27.74	3.5%	49.59	8.8%	19.68	0.6%	28.3	48.5
XXL-RLV, exp. core.: 2 M520 + M520 + M110	29.60	3.3%	51.53	8.4%	21.48	0.5%	30.4	52.0
RLVC4 VTHL Mini-TSTO	7.22	0.5%	11.24	1.5%	6.01	0.1%	8.1	14.0
RLVC4 VTHL TSTO	7.35	0.6%	10.07	2.3%	6.36	0.1%	10.3	17.3
RLVC4 VTHL 3STO	7.77	0.6%	10.60	2.2%	6.73	0.1%	10.7	18.2

Table 6
Life cycle impacts for the different fleets for their cumulated lifetime of 20 years normalised with respect to annual planetary boundaries (PB) from JRC [53]. These are 6.79×10^{11} $kgCO_2$ for climate change (CC) in GWP100, 6.85×10^{11} m^3 for water use (WU). CC is evaluated with the aviation CFs as baseline while CC* accounts for high altitude impacts using the corresponding CFs from Table 2 as described in Section 4.4. For land use, the normalisation is with respect to European agricultural land occupation (ELOP) of 157.4 million hectares (ha) in 2020 from Eurostats.

Fleet	CC [Tg]	CC* [Tg]	WU [km3]	LU [km2]	CC [%PB]	CC* [%PB]	WU [%PB]	LU [%ELOP]
LH_2 VTVL L&XXL	2.684	159.673	3.254	56.369	0.40%	23.52%	0.48%	0.0036%
LCH_4 VTVL L&XXL	6.016	1229.818	6.195	105.201	0.89%	181.12%	0.90%	0.0067%
RLVC4 VTHL	1.829	161.548	2.473	41.852	0.27%	23.79%	0.36%	0.0027%

land use, despite its 4% lower total dry mass. This difference can be explained by the 30% larger propellant mass requirements for the VTVL LH_2 fleet and increased reusability of the RLVC4 fleet. For the VTVL CH_4 fleet, the climate impact was found to be 2–5 times larger than the LH_2 fleets, partially because of BC emissions. This larger footprint was also seen in water and land use, with a 90% higher demand compared to the RLVC4 fleet. These results suggest that propellant choice might be the driving factor when it comes to space transportation eco-design.

The comparison with respect to the planetary boundaries (PB) from JRC [53] shown in Fig. 4 also provides some insights into the scale of the footprint over the fleet lifetime. The climate impacts assessed with the baseline aviation based characterisation factors would be between 0.1%–1% of the annual PB. However, the results in the CC* field characterising high altitude impacts, as further described in Section 4.4, indicate that this can be a large underestimation. For water use, the results would reach almost 1% of the global planetary boundary, or between 6%–15% of the annual European water usage. In terms of land use, the results would be approximately equivalent to the available land to sustain 20,000–60,000 individuals, based on a globally averaged 0.18 arable hectares per capita [54], although they would not reach a significant portion of the total European agricultural land occupation.

Nevertheless, results are dominated by uncertainty. Firstly, the linear nature of the LCA itself might not be applicable to large economic activities with respect to the global and regional background [55], as can be a large fleet of niche reusable space rockets. Additionally, the space foreground and background databases used in this study contain significant uncertainty which can affect the resulting comparisons. Furthermore, the engine exhaust emissions and plume post-combustion phenomena at higher altitudes such as from propellant burning, reentry aero-heating and demise of the expendable stages are highly uncertain, especially for newer methane engines. This, together with the uncertainty around the LCIA factors, may mean that stages with larger overall propellant consumption cause significantly worse impacts. There is also a concerning lack of data regarding fugitive emissions from methane and hydrogen within their extraction, synthesis, storage and loading processes which may dominate the uncertainty on their life cycle impacts. Leakages can also have a significant regional dependency based on the technologies and regulations implemented in each state. The other main source of uncertainty comes from the climate impacts of high altitude BC, water, nitrogen oxides, hydrogen and carbon monoxide. This is clear when comparing the sensitivity to the assumptions in CFs in Section 4.4. In addition, the choice of climate metric significantly affected results; for example, the impacts of the LCH_4 fleet was more than 100% greater when compared within a 20 year time horizon due to fugitive methane emissions and stronger BC impacts over smaller time scales, whereas the RLVC4 performed slightly worse than the LH_2 fleet in terms of global temperature change potential when considered over 100 years.

Another source of uncertainty affecting the comparisons is the cross dependency within impact categories, which has not yet been addressed directly in LCA frameworks. This can be seen through the increased stratospheric radiative forcing from high altitude emissions causing ozone depletion as discussed in Section 4.4. Another possible cross dependency may arise if bio-methane produced at the proposed Kourou launch site is used as fuel, contributing to land use and deforestation if its feedstock is sourced from regional markets [56]. This would lead to an effect on regional and global climates and water budget, affecting the corresponding LCA footprints. Additionally, the impacts of climate change may increase water use as a consequence of more frequent draughts or saline intrusion from sea level rise depleting groundwater sources [57].

4.2. *Contribution analysis*

Figs. 5 and 6 show a contribution analysis from the main activities of the life cycle evaluated with the aviation based CFs from Table 2.

It can be seen how for all launch vehicle types, recurrent activities have a large share of the final impact which might be explained by the omission of infrastructure development. Furthermore, within this study their impacts were independent of stage size. Nevertheless, it cannot be assumed that this would be the same for the XXL class of launch vehicles and for small launchers with easier handling considerations. This non-negligible dependency on stage size is already captured within some cost estimation methodologies [58,59].

Propellant related impacts were also seen to be a significant share of the life cycle impact. This was partly a consequence of the large footprint modelled with the SSSD associated with decontamination activities of the propellant infrastructure after use, and from general handling activities, constituting around two thirds of their impact. Nevertheless, it must be highlighted that the underlying life cycle inventory data might be biased towards spacecrafts and upper stages as a consequence of larger data availability. These are composed of significantly less propellant by mass and mostly entail hydrazine and other hazardous fuels with complex handling and decontamination

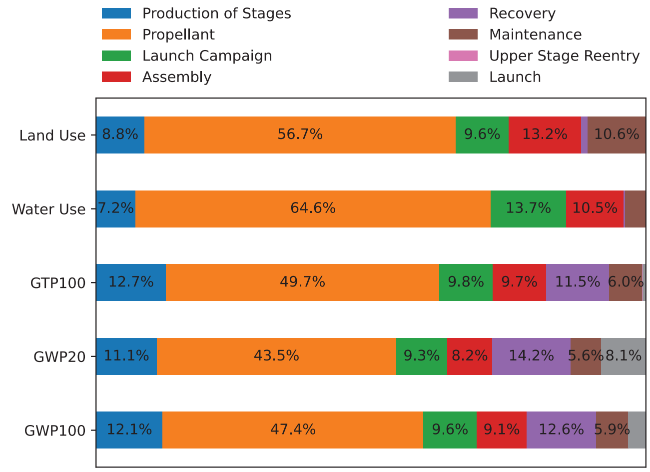


Fig. 5. Contribution analysis to the different environmental impacts for the LH_2 VTVL L&XX fleet type evaluated with the aviation based CFs from Table 2.

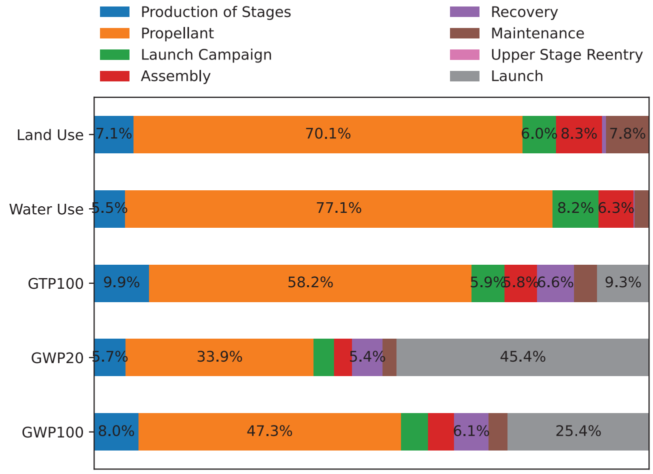


Fig. 6. Contribution analysis to the different environmental impacts for the LCH_4 VTVL L&XX fleet type evaluated with the aviation based CFs from Table 2.

requirements. This, combined with the linearity assumption within LCAs, might mean that the processes are significantly overestimating the associated effort for large liquid launch vehicles, which typically employ relatively benign propellant and can benefit from economies of scale. However, this overestimation could be counterbalanced by the relatively low leakage rates assumed for hydrogen and methane, as explained in Section 3.3.

From the contribution analysis, it also seems that the impacts from the launch event are small for hydrogen fuelled launchers, but dominate for methane powered vehicles because of the assumed BC emissions. It should be noted that the later exhaust currently has large uncertainty for methalox engines, given the lack of measurements and the complex plume post-combustion of some BC at lower altitudes with larger oxygen supply [3]. The estimated launch event impacts, however, may be an underestimation, given the identified larger climate impacts from BC emissions emitted by launch vehicles compared to its emissions from other industries [2,4]. Stratospheric water emissions may also have a significant climatic impact, as has been seen in past studies for hydrogen powered hypersonic aircraft [60].

In addition, it can be seen how the choice of climate metric affects results significantly. For the methane powered launchers assessed with the GWP100 methodology, the impacts from the launch event were around one quarter of the total life cycle. However, this share increased to almost a half when assessing with the integrated global warming potential over a 20 year time horizon, highlighting the extremely high sensitivity to the underlying methodology, particularly with regards to the treatment of launch related exhaust emissions.

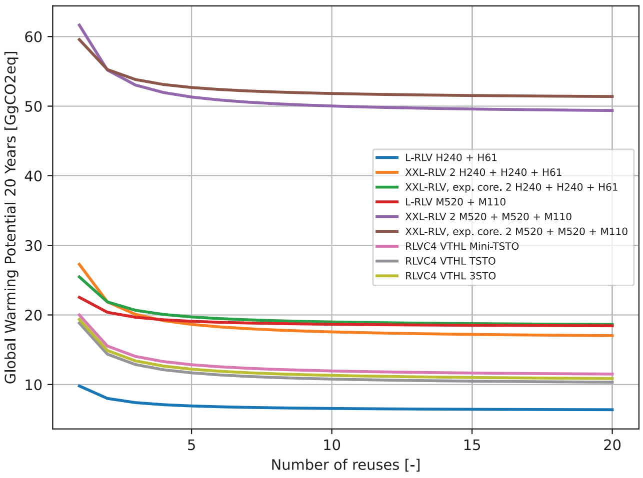


Fig. 7. Life cycle emissions of the different reusable launch vehicle types for 1 to 20 reuses assessed with the extended global warming potential over 20 years impact assessment method.

4.3. *Sensitivity of climate impact to reuse rates*

Fig. 7 shows the sensitivity of the GWP20 impacts to the assumed reuse rates. Although a large sensitivity is observed with a low number of reuses, the overall reduction achieved through reusability quickly settles to between 30%–40% for the LH_2 fleets and 20% for the CH_4 fleet. This low fraction is explained by the large contribution of recurrent activities such as launch emissions and recovery processes to the total impact, as shown in Section 4.2. In fact, it might not be clear if reusing stages could be more sustainable from the carbon footprint point of view, as it adds new recurring activities as recovery operations, refurbishment and maintenance which translates into lower performance after factoring in the additional inert and propellant mass. This would also add to the high altitude atmospheric impact burden which may be underestimated with the aviation based CFs [5,19], although a possible trade off might exist with the reentry demise emissions from the expendable counterparts. The CF sensitivity is further addressed in the following section.

4.4. *Sensitivity to characterisation factors*

The final sensitivity assessment concerned the CFs presented in Section 3. The baseline LCIA method used for this study employed CFs based on averaged aviation emissions and impacts at cruise altitude. For launch vehicles, this might be a significant underestimation. However, a lack of understanding around the most applicable climate metrics complicate the application of an LCA methodology. Within this study, two CFs sensitivities were performed, as reported in Table 2. The first characterised launch emissions as if they were emitted in the lower troposphere. This showed reduced impacts, especially in GWP20. The second characterised high altitude emissions with GWP100 values derived from the Bern model [61] by assuming an exponential decay with an averaged lifetime of 4 years from instantaneous radiative forcings normalised per kg of exhaust obtained from past climate simulations [2,60], as described in an accompanying publication [28]. However, these values should be taken with caution as high uncertainty remains around the radiative forcing of launch vehicle emissions and this approach should be applied to the relaxed radiative forcing after stratospheric adjustment. It should also be noted that GWP does not translate directly

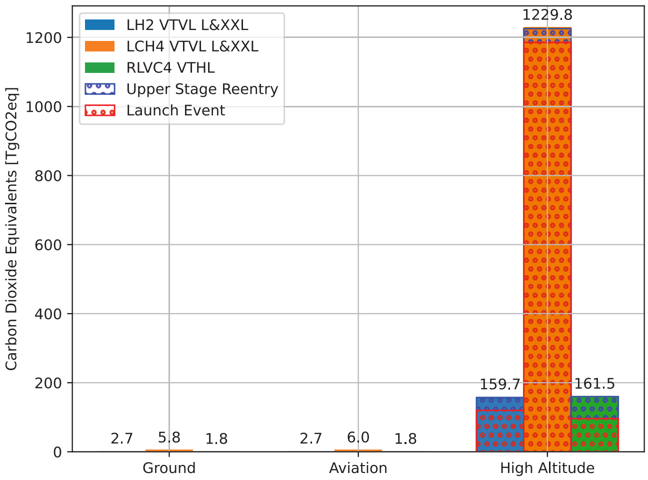


Fig. 8. Fleet total climate change life cycle impacts in GWP100 assessed with different CFs.

to global average temperature change, since the mechanisms through which stratospheric warming affects the climate differ considerably from those of GHG emissions in the troposphere. Nevertheless, GWP serves as a potential indication as to how important launch emissions might be when compared to ground GHG emissions within an LCA.

Results from both sensitivities in terms of GWP100 can be seen in Table 6 and Fig. 8. The corresponding GWP20 results had a 2.5× larger footprint. Here, it is seen how the previous relative advantage of the RLVC4 fleet when compared to the VTVL LH_2 fleet is cancelled (and even reversed to a 1.1% larger footprint) as a consequence of the demised aluminium oxide emissions resulting from its higher total dry mass. It is also observed how the climate impact may be approximately 100× larger for the LH_2 fleets and up to 1000× larger for the CH_4 fleet as a consequence of the stratospheric warming caused by high altitude emissions of non-CO_2 pollutants. This would put its impact in the Gt range, making it comparable to the Earth's carrying capacity given by its annual planetary boundary for CO_2 emissions [62]. The methalox fleet would emit in its entire $\approx$ 20 year lifetime approximately the same amount of CO_2eq as the annual emissions of global commercial aviation. Nevertheless, this result is dominated by uncertainty for two main reasons. Firstly, the fleet performance can change according to different technologies which may affect the associated BC emissions from methalox engines (such as staged combustion). In addition, the resulting stratospheric radiative forcing might not translate directly into global temperature change. There is a possibility of surface cooling from stratospheric warming from BC emissions [8] and of tropospheric warming from stratospheric water emissions [60]. Furthermore, stratospheric radiative forcing does not only influence climate, but may also deplete the ozone layer together with other pollutants emitted by launchers and demising spacecraft [3,4,8,63].

A major finding is that launch event emissions dominate, followed by reentry emissions. This may have large implications for previous space sector LCAs both in terms of the absolute impact (underestimated by 2 to 3 orders of magnitude) and in the identification of the underlying cause. These findings may also lead to a complete redefinition of what space sector sustainability may actually be. For example, in terms of launcher sustainability, a previous LCA conducted [5] showed how large reusability rates could eventually achieve break-evens in climate impact, in spite of more ground activities and larger propellant consumption. These results suggest that the trade-off would be inexistent, and that reusing launcher components would always lead to larger climate impacts given the lower performance and higher non-CO_2 emissions in the stratosphere. In the same way, CO_2-neutral "sustainable aviation fuels" could fail in achieving any appreciable climate impact reduction unless they can also achieve reduced stratospheric BC, water and NO_x emissions.

It must be noted that the quantities of stratospheric BC emissions considered might be of such magnitude (around 100 Mg) when compared with background concentrations that the linear assumption within LCA might fail to adequately estimate its aggregate impact. This effect has already been observed in past studies on aviation NO_x emissions leading to different or even negative in climatic impacts as a consequence of the modified atmospheric composition [64]. For example, climate simulations from nuclear war between major countries address the injection of stratospheric BC emissions in the order of several Tg and indicate potential surface cooling effects of several degrees associated with nuclear winters [65]. A possible non-linear effect might also be the case with reentry emissions of aluminium oxides and other metal compounds, as these may overshadow the natural injection by meteorites [46], or even from the direct high altitude heat emissions from the energetic launch and reentry operations. The linearity of the radiative forcing from launchers BC emissions was partially addressed in Ref. [3]. In addition, it also neglects effects from induced cloudiness, which already dominates the uncertainty in the climate response for aircraft [27] at short time scales. These issues highlight the need to complement LCAs with climate simulations in order to validate the environmental impact of large space activities. It is also necessary to derive adequate climate metrics for launch and reentry emissions, and compare different climate metrics when assessing the possible uncertainty, given the large sensitivity to time horizons.

5. Conclusions

This work analysed, for the first time, the environmental footprint of different reusable launch vehicle fleets which could serve future Europe's needs. LCA results were contextualised to enhance the understanding of the scale of the impact.

The LH_2 fleets had the lowest impact in all impact categories showing that propellant choice is the main differentiation factor when it comes to environmental criteria. The RLVC4 also achieved an approximately 30% lower environmental footprint in water and land use when compared to the VTVL LH_2 fleet given its higher performance. When high altitude GWP100 CFs were considered for BC, water and aluminium oxide emissions in the stratosphere, GWP climate impacts were up to 1000× higher, reaching magnitudes comparable to those of global annual commercial aviation and potentially exceeding Earth's carrying capacity defined by its planetary boundaries, especially for the CH_4 combination. Given that the burden would only correspond to the European potential contribution from launchers, these findings highlight the urgent need of addressing global launch vehicle emissions from all spacefaring nations. This becomes more concerning when considering the current low state of knowledge around their climatic response, its possible diverse influences on the Earth system, and the nature of the GWP metric itself, complicating the direct translation into a simplified global surface average temperature change criterion. This uncertainty was evident when comparing the different climate metrics from this study; as the LCH_4 fleet had a 100%–250% higher impacts when considered within a 20 year time horizon as a result of fugitive methane emissions and stronger BC impacts. There also remains significant uncertainty on the exhaust emissions of BC for methalox combustion, plume post-combustion modelling and the impacts at higher altitudes from propellant burning, reentry aero-heating, demise of the expendable stages, and fugitive life-cycle emissions from the different fuels.

Future studies on the sustainability of launchers should address all these aspects to ensure an accurate quantification of its environmental performance and uncertainty. Studies could also perform prospective LCAs to address future changes in background processes as with the possible uptake of sustainable hydrogen and methane fuel production.

Furthermore, to support eco-design efforts, it is also necessary to determine adequate climate change metrics and an overall sustainability score which can aggregate the different faces of its climatic response. In addition, studies could also consider other impact categories such as stratospheric ozone depletion, and further inventory processes, such as the development phases with qualification flights; test firings; travelling; treatment of infrastructure; and the transportation of stages between Europe and French Guyana for production and maintenance operations.

CRediT authorship contribution statement

Guillermo J. Dominguez Calabuig: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Andrew Wilson:** Funding acquisition, Investigation, Methodology, Project administration, Software, Supervision, Validation. **Sifeng Bi:** Funding acquisition, Project administration, Supervision. **Massimiliano Vasile:** Supervision, Funding acquisition, Project administration. **Martin Sippel:** Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Supervision. **Martin Tajmar:** Funding acquisition, Project administration, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] J. Wilken, Cost estimation for launch vehicle families considering uncertain market scenarios, Acta Astronaut. 216 (2024) 15–26, http://dx.doi.org/10.1016/j.actaastro.2023.12.035.

[2] M.N. Ross, P.M. Sheaffer, Radiative forcing caused by rocket engine emissions, Earth's Future 2 (4) (2014) 177–196, http://dx.doi.org/10.1002/2013EF000160.

[3] C.M. Maloney, R.W. Portmann, M.N. Ross, K.H. Rosenlof, The climate and ozone impacts of black carbon emissions from global rocket launches, J. Geophys. Res.: Atmos. 127 (12) (2022) http://dx.doi.org/10.1029/2021JD036373.

[4] R.G. Ryan, E.A. Marais, C.J. Balhatchet, S.D. Eastham, Impact of rocket launch and space debris air pollutant emissions on stratospheric ozone and global climate, Earth's Future 10 (6) (2022) http://dx.doi.org/10.1029/2021EF002612.

[5] G.J. Dominguez Calabuig, L. Miraux, A.R. Wilson, A. Sarritzu, A. Pasini, Eco-design of future reusable launchers: insight into their lifecycle and atmospheric impact, in: 9th European Conference for Aeronautics and Space Sciences, EUCASS, 2022.

[6] L. Miraux, A.R. Wilson, G.J. Dominguez Calabuig, Environmental sustainability of future proposed space activities, Acta Astronaut. 200 (2022) 329–346, http://dx.doi.org/10.1016/j.actaastro.2022.07.034.

[7] B. Alcott, Jevons' paradox, Ecol. Econom. 54 (1) (2005) 9–21, http://dx.doi.org/10.1016/j.ecolecon.2005.03.020.

[8] M.N. Ross, K.L. Jones, Implications of a growing spaceflight industry: Climate change, J. Space Saf. Eng. 9 (3) (2022) 469–477, http://dx.doi.org/10.1016/j.jsse.2022.04.004.

[9] M. Ross, D. Toohey, M. Peinemann, P. Ross, Limits on the space launch market related to stratospheric ozone depletion, Astropolitics 7 (1) (2009) 50–82, http://dx.doi.org/10.1080/14777620902768867.

[10] C. Voigt, U. Schumann, K. Graf, K.-D. Gottschaldt, Impact of rocket exhaust plumes on atmospheric composition and climate - An overview, Prog. Propuls. Phys. 4 (2013).

[11] E.J.L. Larson, R.W. Portmann, K.H. Rosenlof, D.W. Fahey, J.S. Daniel, M.N. Ross, Global atmospheric response to emissions from a proposed reusable space launch system, Earth's Future 5 (1) (2017) 37–48, http://dx.doi.org/10.1002/2016EF000399.

[12] J.A. Dallas, S. Raval, J.P. Alvarez Gaitan, S. Saydam, A.G. Dempster, The environmental impact of emissions from space launches: A comprehensive review, J. Clean. Prod. 255 (2020) 120209, http://dx.doi.org/10.1016/j.jclepro.2020.120209.

[13] M.N. Ross, M. Mills, D. Toohey, Potential climate impact of black carbon emitted by rockets, Geophys. Res. Lett. 37 (2010).

[14] I.W. Kokkinakis, D. Drikakis, Atmospheric pollution from rockets, Phys. Fluids 34 (5) (2022) 056107, http://dx.doi.org/10.1063/5.0090017.

[15] A. Chanoine, Environmental impacts of launchers and space missions, in: Cleanspace Industrial Days, 2017.

[16] A. Gallice, T. Maury, E. del Olmo, Environmental impact of the exploitation of the Ariane 6 launcher system, in: Cleanspace Industrial Days, 2018.

[17] Y. Romaniw, B. Bras, Environmental burdens and the light-weighting of rockets, in: ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, 2013, http://dx.doi.org/10.1115/DETC2013-13310.

[18] S.S. Neumann, Environmental Life Cycle Assessment of Commercial Space Transportation Activities in the United States (Ph.D. thesis), University of Texas at Arlington, 2018.

[19] G.J. Dominguez Calabuig, J. Wilken, Pre-conceptual staging trade-offs of reusable launch vehicles, in: 9th European Conference for Aeronautics and Space Sciences, EUCASS, 2022.

[20] A.R. Wilson, Advanced Methods of Life Cycle Assessment for Space Systems (Ph.D. thesis), University of Strathclyde, 2019.

[21] M. Sippel, S. Stappert, S. Callsen, K. Bergmann, I. Dietlein, L. Bussler, Family of launchers approach vs. "big-size-fits-all", in: IAC-22-D2.4.1, 2022.

[22] M. Sippel, S. Callsen, J. Wilken, K. Bergmann, I. Dietlein, L. Bussler, G.J. Dominguez Calabuig, S. Stappert, Outlook on the new generation of European reusable launchers, in: ASCenSIon Conference, Dresden, 12-14th September, 2023, 2023.

[23] M. Sippel, S. Stappert, V. Pastrikakis, V. Barannik, D. Maksiuta, L. Moroz, Systematic studies on reusable staged-combustion rocket engine SLME for European applications, in: Space Propulsion 2022, Estoril, Portugal, 2022.

[24] M. Sippel, S. Singh, S. Stappert, Summary of H2020-project FALCon, in: Aerospace Europe Conference, Lausanne, Switzerland, 2023.

[25] E. Pauer, B. Wohner, M. Tacker, The influence of database selection on environmental impact results. life cycle assessment of packaging using GaBi, ecoinvent 3.6, and the environmental footprint database, Sustainability 12 (23) (2020) 9948, http://dx.doi.org/10.3390/su12239948.

[26] G. Myhre, D. Shindell, F.M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, H. Zha, Anthropogenic and natural radiative forcing, in: IPCC (Ed.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I To the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

[27] D.S. Lee, D.W. Fahey, A. Skowron, M.R. Allen, U. Burkhardt, Q. Chen, S.J. Doherty, S. Freeman, P.M. Forster, J. Fuglestvedt, A. Gettelman, R.R. de León, L.L. Lim, M.T. Lund, R.J. Millar, B. Owen, J.E. Penner, G. Pitari, M.J. Prather, R. Sausen, L.J. Wilcox, The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018, Atmos. Environ. (Oxford, England : 1994) 244 (2021) 117834, http://dx.doi.org/10.1016/j.atmosenv.2020.117834.

[28] G.J. Dominguez Calabuig, C. Berk Senel, O. Karatekin, O. Temel, A.R. Wilson, M. Vasile, S. Bi, A life cycle perspective of the climate forcing from black carbon emissions of starship and falcon 9 launchers, in: ASCenSIon Conference, Dresden, 12-14th September, 2023.

[29] L. Miraux, Derivation of analog GWP coefficients for the high altitude effects of launches, in: Workshop on Life Cycle Assessment of Space Transportation Systems, 4-6 July, 2023, Stuttgart, 2023.

[30] S.C. Sherwood, V. Dixit, C. Salomez, The global warming potential of near-surface emitted water vapour, Environ. Res. Lett. 13 (10) (2018) 104006, http://dx.doi.org/10.1088/1748-9326/aae018.

[31] G. Lammel, H. Graßl, Greenhouse effect of NOX, Environ. Sci. Pollut. Res. 2 (1) (1995) 40–45, http://dx.doi.org/10.1007/BF02987512.

[32] R.K. Fagodiya, H. Pathak, A. Kumar, A. Bhatia, N. Jain, Global temperature change potential of nitrogen use in agriculture: A 50-year assessment, Sci. Rep. 7 (1) (2017) http://dx.doi.org/10.1038/srep44928.

[33] D. Hauglustaine, F. Paulot, W. Collins, R. Derwent, M. Sand, O. Boucher, Climate benefit of a future hydrogen economy, Commun. Earth Environ. 3 (1) (2022) http://dx.doi.org/10.1038/s43247-022-00626-z.

[34] J. Hansen, M. Sato, P. Kharecha, G. Russell, D.W. Lea, M. Siddall, Climate change and trace gases, Phil. Trans. R. Soc. A 365 (1856) (2007) 1925–1954, http://dx.doi.org/10.1098/rsta.2007.2052.

[35] A.-M. Boulay, J. Bare, L. Benini, M. Berger, M.J. Lathuillière, A. Manzardo, M. Margni, M. Motoshita, M. Núñez, A.V. Pastor, B. Ridoutt, T. Oki, S. Worbe, S. Pfister, The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE), Int. J. Life Cycle Assess. 23 (2) (2017) 368–378, http://dx.doi.org/10.1007/s11367-017-1333-8.

[36] M. Huijbregts, Z. Steinmann, P. Elshout, G. Stam, F. Verones, M. Vieira, A. Hollander, M. Zijp, R. van Zelm, ReCiPe 2016A Harmonized Life Cycle Impact Assessment Method at Midpoint and Endpoint Level. Report I: Characterization, Tech. Rep., National Institute for Public Health and the Environment, RIVM Report 2016-0104, 2016.

[37] D.J. Wuebbles, Weighing functions for ozone depletion and greenhouse gas effects on climate, Ann. Rev. Energy Environ. 20 (1) (1995) 45–70, http://dx.doi.org/10.1146/annurev.eg.20.110195.000401.

[38] A.R. Wilson, S.M. Serrano, K.J. Baker, H.B. Oqab, G.B. Dietrich, M.L. Vasile, T. Soares, L. Innocenti, From life cycle assessment of space systems to environmental communication and reporting, in: 72nd International Astronautical Congress, IAC, 2022.

[39] R.W. Howarth, M.Z. Jacobson, How green is blue hydrogen? Energy Sci. Eng. 9 (10) (2021) 1676–1687, http://dx.doi.org/10.1002/ese3.956.

[40] I.B. Ocko, S.P. Hamburg, Climate consequences of hydrogen leakage, Atmos. Chem. Phys. Discuss. (2022) http://dx.doi.org/10.5194/acp-2022-91.

[41] T. Weidner, V. Tulus, G. Guillén-Gosálbez, Environmental sustainability assessment of large-scale hydrogen production using prospective life cycle analysis, Int. J. Hydrog. Energy 48 (22) (2023) 8310–8327, http://dx.doi.org/10.1016/j.ijhydene.2022.11.044.

[42] S. Stappert, J. Wilken, L. Bussler, M. Sippel, A systematic comparison of reusable first stage return options, in: 8th European Conference for Aeronautics and Space Sciences, EUCASS, 2019.

[43] G.J. Dominguez Calabuig, Conceptual Cost Estimation for Recovery and Refurbishment Operations of Reusable Launch Vehicles, Tech. Rep., DLR, 2019.

[44] C.A. Kontovas, Integration of air quality and climate change policies in shipping: The case of sulphur emissions regulation, Marine Policy 113 (2020) 103815, http://dx.doi.org/10.1016/j.marpol.2020.103815.

[45] J. Fuglestvedt, T. Berntsen, V. Eyring, I. Isaksen, D.S. Lee, R. Sausen, Shipping emissions: from cooling to warming of climate-and reducing impacts on health, Environ. Sci. Technol. 43 (24) (2009) 9057–9062, http://dx.doi.org/10.1021/es901944r.

[46] L. Schulz, K.-H. Glassmeier, On the anthropogenic and natural injection of matter into Earth's atmosphere, Adv. Space Res. 67 (3) (2021) 1002–1025, http://dx.doi.org/10.1016/j.asr.2020.10.036.

[47] A. Boley, M. Byers, Satellite mega-constellations create risks in Low Earth Orbit, the atmosphere and on Earth, Sci. Rep. 11 (2021).

[48] C. Park, J.V. Rakich, Equivalent-cone calculation of nitric oxide production rate during space shuttle re-entry, Atmos. Environ.(1967) 14 (8) (1980) 971–972, http://dx.doi.org/10.1016/0004-6981(80)90011-6.

[49] National Academies of Sciences Engineering and Medicine, Commercial Space Vehicle Emissions Modelling, Transportation Research Board, 2021, http://dx.doi.org/10.17226/26142.

[50] A.A. Alexeenko, N.E. Gimelshein, D.A. Levin, R.J. Collins, R. Rao, G.V. Candler, S.F. Gimelshein, J.S. Hong, T. Schilling, Modeling of flow and radiation in the Atlas Plume, J. Thermophys. Heat Transfer 16 (1) (2002) 50–57, http://dx.doi.org/10.2514/2.6651.

[51] F.S. Simmons, Rocket Exhaust Plume Phenomenology, Aerospace Corporation, 2000.

[52] A. Viviani, G. Pezzella, Aerodynamic and Aerothermodynamic Analysis of Space Mission Vehicles, Springer aerospace technology, Springer, Cham [Switzerland], 2015.

[53] S. Sala, L. Benini, E. Crenna, M. Secchi, Global Environmental Impacts and Planetary Boundaries in LCA: Data Sources and Methodological Choices for the Calculation of Global and Consumption-Based Normalisation Factors, Tech. rep.,JRC, European Comission, jRC Technical report, 2016.

[54] The World Bank, Arable Land (Hectares Per Person) in 2021.[AG.LND.ARBL.HA.PC], Tech. Rep, 2024, URL https://data.worldbank.org/indicator/AG.LND.ARBL.HA.PC.

[55] R. Heijungs, S. Suh, The computational structure of life cycle assessment, Eco-Effic. Ind. Sci. (2002) http://dx.doi.org/10.1007/978-94-015-9900-9.

[56] L. Ferrante, P.M. Fearnside, The Amazon: biofuels plan will drive deforestation, Nature 577 (7789) (2020) 170, http://dx.doi.org/10.1038/d41586-020-00005-8.

[57] S. Jasechko, D. Perrone, H. Seybold, Y. Fan, J.W. Kirchner, Groundwater level observations in 250,000 coastal US wells reveal scope of potential seawater intrusion, Nature Commun. 11 (1) (2020) http://dx.doi.org/10.1038/s41467-020-17038-2.

[58] D.E. Koelle, The transcost-model for launch vehicle cost estimation and its application to future systems analysis, Acta Astronaut. 11 (12) (1984) 803–817, http://dx.doi.org/10.1016/0094-5765(84)90100-0.

[59] S. Stappert, J. Wilken, G.J. Dominguez Calabuig, M. Sippel, Evaluation of parametric cost estimation in the preliminary design phase of reusable launch vehicles, in: 9th European Conference for Aeronautics and Space Sciences, EUCASS, 2022.

[60] J.F. Pletzer, D. Hauglustaine, Y. Cohen, P. Jöckel, V. Grewe, The Climate Impact of Hypersonic Transport, EGUsphere, 2022, http://dx.doi.org/10.5194/egusphere-2022-285, preprint.

[61] IPCC (Ed.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.

[62] E. Crenna, L. Benini, S. Sala, M. Secchi, Global Environmental Impacts and Planetary Boundaries in LCA, EUR, Scientific and technical research series, vol. 28371, Publications Office, Luxembourg, 2016.

[63] L. Miraux, Environmental limits to the space sector's growth, Sci. Tot. Environ. 806 (Pt 4) (2022) 150862, http://dx.doi.org/10.1016/j.scitotenv.2021.150862.

[64] E. Terrenoire, D.A. Hauglustaine, Y. Cohen, A. Cozic, R. Valorso, F. Lefèvre, S. Matthes, Impact of present and future aircraft NO_x and aerosol emissions on atmospheric composition and associated direct radiative forcing of climate, Atmos. Chem. Phys. 22 (18) (2022) 11987–12023, http://dx.doi.org/10.5194/acp-22-11987-2022.

[65] J. Coupe, C.G. Bardeen, A. Robock, O.B. Toon, Nuclear winter responses to nuclear war between the United States and Russia in the whole atmosphere community climate model version 4 and the Goddard Institute for Space Studies ModelE, J. Geophys. Res.: Atmos. 124 (15) (2019) 8522–8543, http://dx.doi.org/10.1029/2019JD030509.