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Eco-design of future reusable launchers: insight into their life cycle and atmospheric impact

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Abstract

Reusable launch vehicles (RLV) are slowly emerging as a solution to reduce space access costs, bringing potential benefits from novel breakthrough space application. Whilst space presents an ideal platform for addressing global issues, it raises an "adaptation-mitigation dilemma". Launch vehicles are the only anthropogenic object emitting directly into every layer of the atmosphere, and reusability may introduce additional burdens. Although it may ensure a rational use of materials through the recycling of major components, its potential sustainability gains with respect to equivalent expendable launch vehicles (ELV) has not been quantified. The correct understanding of these are therefore critical to ensure sustainable design choices for space transportation.

This study reviews current state of knowledge on launchers environmental impact and eco-design before introducing a preliminary life cycle and atmospheric impact assessment of the different technologies for first stage reusabiltiy. Reusabiltiy showed possible early reductions in material resource depletion which was independent of propellant choice and recovery strategies. In terms of climate forcing, reusability was only beneficial when fully carbon neutral propellant production was assumed for hydrolox, ammolox technologies, and possibly for methalox if soot production is kept under sustainable limits. VTHL performing In-Air-Capturing recoveries also showed reduced climate forcing potential. Stratospheric ozone depletion potential was estimated to increase by 18-34 % for VTVL vehicles, and 12-16% for VTHL with respect to ELV. In addition, high sensitivity with mixture ratios, flight profiles, staging conditions and aerodynamic capabilities was identified, which require detailed assessments with higher fidelity design methods. Future launch impacts from large scale space activities were also estimated to no longer be negligible, although some margin for mitigation exists among the various design options, and recent regulatory developments internalizing climate change costs might significantly affect the business case of RLVs.

In addition, high altitude atmospheric impacts, particularly those from soot emissions, appear to dominate the potential life cycle impact and uncertainty, especially for hydrocarbon fuelled launch vehicles. This is further exacerbated by the commonly used but unsuitable weighting based on aviation and ground based emissions. These might affect the absolute and relative comparisons significantly and therefore, results from this study must be taken with caution. Future studies should employ state of art atmospheric modelling and adequate approaches to weight the various life cycle phases, enabling design for mitigation while avoiding burden shifts.

Nomenclature

Acronyms

DRL	Down Range Landing
EI	Emmisivity Index
ELV	Expendable Launch Vehicle
GWP	Global Warming Potential
IAC	In Air Capturing
LCA	Life Cycle Assessment
MDIO	Mass Disposed in Ocean
MRDP	Material Resource Depletion Potential
ODP	Ozone Depletion Potential
RF	Radiative Forcing
RLV	Reusable Launch Vehicle

RTLS	Return To Launch Site
SSSD	Strathclyde Space Systems Database
TSTO	Two Stages To Orbit
VTHL	Vertical Take-off Horizontal Landing
VTVL	Vertical Take-off Vertical Landing

Symbols

d	Diameter or Downrange	m
I_{sp}	Specific Impulse	s
l	Length	m
m_d	Dry mass	Mg
m_L	Payload mass	Mg
m_T	Total mass	Mg
m_p	Propellant mass	Mg
O/F	Oxidizer to fuel ratio	-

1. Introduction

The launch sector is significantly developing worldwide through public and private investments aimed at expanding national space capabilities. As a result, the number of launches per year is drastically increasing. This promotes a virtuous cycle of investments and technological developments.

At the same time, humanity is becoming aware of its environmental limits, especially as climate change continues to unravel. Whilst space presents an ideal platform for addressing global issues, it raises an "adaptation-mitigation dilemma". Launch vehicles are the only anthropogenic object emitting directly into every layer of the atmosphere. As a consequence of increasing global launch rates from future space activities,[1] public awareness may eventually steer policy and regulations in the sector, placing an added importance on being able to scientifically quantify environmental impacts of launchers.

The atmospheric impact of analogous commercial aviation has been studied for decades, with an estimated contribution to global warming 3.5%, mostly from non-CO_2 impacts as NO_x, cirrus cloud formations and black carbon emissions,.[2] Research on supersonic and hypersonic aviation, a possibly closer analogy to launchers, shows their climate impact magnifies with increasing flying speeds and altitudes,[3,4] with non-CO_2 emissions covering a key role on climate forcing and stratospheric ozone depletion.[5]

For launch vehicles, it is known that their atmospheric impact ranges from direct alteration of stratospheric ozone concentrations, creation of large polar mesospheric cloud,[6] and injection of climate-altering long-living greenhouse gasses and aerosol pollutants in the upper atmosphere.[7–9] Previous attempts of life cycle assessments (LCA) considered the launch event impacts mostly in terms of stratospheric ozone depletion, but omitted the climate effects of non-launch event phases.[10] On the opposite, other studies considered the climate effects of launch events negligible,[11] assumption derived from presuming only CO_2 and CO emissions effects with ground-based metrics, and omitting effects of H_2O, NO_x and key aerosols in the upper atmosphere layers. In the last few years, the potential impact has been recognized and outlined by The Aerospace Corporation in many studies,[7,12] especially regarding stratospheric ozone depletion,[13,14] with some measurements carried out on local scales.

The environmental impact varies considerably depending on the launch vehicle characteristics. The influencing parameters are many: materials, propellants, recovery strategy, aerodynamic design and flight profiles. These determine emission profiles, exhaust composition, production of NO_2 from re-entry shockwaves and impacts of demisable material. Some studies[7,14] have identified large differences in atmospheric impacts between hybrid rocket engines and hydrogen fueled spaceplanes, highlighting the need for future studies on the different options. Y. Romaniw et al[15] examined the environmental impact of light weighting structural components of ELVs, while S. S. Neumann[16] assessed differences in environmental impacts between ELVs and RLVs. Various propellant options were already studied by M. N. Ross et al[7] in terms of atmospheric radiative forcing assuming similar propellant mass. However, impacts per mission and payload mass could vary considerably. For example, a water based reusable launcher has been proposed with only water vapour emissions,[17] but its propulsion inefficiency resulting in higher exhaust masses and stage dry mass could lead to larger atmospheric and life cycle impacts when compared to some alternatives.

This study assesses various propellant choices and recovery strategies from various RLVs designed for the same target payload in an accompanying paper.[18] The various system design choices are described in Section Section 2. Section Section 3 analyses the LCA methodology, describing the source of the data and outlining the different types of direct emissions in the atmosphere, mainly deriving by combustion processes. Section Section 4 assesses the life cycle impact on the environment of a launching system, followed by a sensitivity assessment on critical aspects, a comparison with past studies and future projects, and concluded with a dedicated remark on the limitations of the study. This is finalized by conclusions and recommendations for further work on environmental assessment of launchers and possible eco-design options in Section 5.

2. Assumed Launch Vehicles

In this study, various propellant and re-usability choices are assessed in terms of performance, cost and environmental impacts. The reference system is a Two Stage to Orbit (TSTO) vehicle with a reusable first stage delivering M_L = 20

Table 1: Specific Impulse for the first and second stage, and oxidizer to fuel ratios (O/F) for the different propellant combinations[18]

Fuel	Oxidizer	I_{sp} [s]		O/F
		Stage 1	Stage 2	
Hydrogen	Oxygen	415	460	5.50
Methane	Oxygen	335	375	3.25
Kerosene	Oxygen	325	365	2.70
Propane	Oxygen	331	371	2.90
Ammonia	Oxygen	310	345	1.40

Table 2: ELV launchers analysed. From Dominguez C.G.J. et al[18]

Propellant		Hydrolox	Methalox	Kerolox	Propalox	Ammolox
Stage 1	m_T [Mg]	295	540	581	557	757
	m_d [Mg]	22	28	27	28	36
	m_p [Mg]	273	512	554	529	721
	l [m]	57	53	50	51	58
Stage 2	m_T [Mg]	68	103	107	105	118
	m_d [Mg]	6	6	6	6	7
	m_p [Mg]	62	97	101	99	111
	l [m]	21	17	16	17	17
Launcher	m_T [Mg]	387	667	713	686	900
	l [m]	90	82	78	80	86
	d [m]	5.7	5.3	5.0	5.1	5.8

Table 3: VTVL launchers analysed. From Dominguez C.G.J. et al[18]

Propellant		Hydrolox		Methalox		Kerolox		Propalox		Ammolox	
Recovery Type		RTLS	DRL	RTLS	DRL	RTLS	DRL	RTLS	DRL	RTLS	DRL
Stage 1	m_T [Mg]	335	364	614	638	654	692	631	652	894	897
	m_d [Mg]	30	32	38	40	38	40	38	39	52	52
	$m_{p,a}$ [Mg]	277	313	527	564	564	613	542	577	774	794
	$m_{p,r}$ [Mg]	25	15	42	29	45	32	45	29	59	42
	l [m]	59	61	55	56	52	53	53	54	61	61
	d_{drl} [km]		546		585		610		588		573
Stage 2	m_T [Mg]	114	79	200	146	217	154	210	152	259	198
	m_d [Mg]	10	7	11	8	11	8	11	9	13	10
	$m_{p,a}$ [Mg]	103	70	186	135	202	143	196	141	242	184
	$m_{p,r}$ [Mg]	1	1	1	1	1	1	1	1	2	1
	l [m]	29	22	26	21	25	20	26	21	27	22
Launcher	m_T [Mg]	474	467	839	809	895	871	867	829	1179	1121
	l [m]	100	94	93	88	89	84	91	86	99	94
	d [m]	5.9	6.1	5.5	5.6	5.2	5.3	5.3	5.4	6.1	6.1

Mg of payload to Low Earth Orbit (LEO), similar to Ariane 5/6. Various reusable first stage options were explored::

- Ballistic Vertical Take Off and Vertical Landing (VTVL) with both Return to Launch Site (RTLS) and Down Range Landing (DRL) manoeuvres landing in a floating barge and being towed back by a tugboat. Equivalent of SpaceX's Falcon 9 technology.
- Winged Vertical Take Off and Horizontal Landing (VTHL) performing a rocket boostback maneouvre for RTLS, and an In-Air Capturing (IAC) recovery manoeuvres with an aircraft (for DRL), as studied by DLR.[19]

Several fuels where assessed in combination with oxygen. These include hydrogen, ammonia, and 3 hydrocarbon fuels; kerosene (RP-1), methane and propane. The design method ensuring the same payload mass is based on an optimal staging methodology extended to account for reusability.[18]

Table 4: VTHL launchers analysed. From Dominguez C.G.J. et al[18]

Propellant		Hydrolox		Methalox		Kerolox		Propalox		Ammolox	
Recovery Type		RTLS	DRL	RTLS	DRL	RTLS	DRL	RTLS	DRL	RTLS	DRL
Stage 1	m_T [Mg]	305	373	582	650	596	670	585	637	832	857
	m_d [Mg]	40	49	52	58	49	55	50	55	69	71
	$m_{p,a}$ [Mg]	255	321	502	587	523	609	509	577	725	778
	$m_{p,r}$ [Mg]	7		23		19		21		30	
	l [m]	57	61	54	56	50	52	52	53	59	59
	d_{drl} [km]		589		773		676		738		738
Stage 2	m_T [Mg]	126	76	219	115	240	128	227	129	307	163
	m_d [Mg]	10	7	12	7	12	7	12	7	15	9
	$m_{p,a}$ [Mg]	114	68	204	106	225	119	211	119	287	152
	$m_{p,r}$ [Mg]	1	1	1	1	1	1	1	1	2	1
	l [m]	33	22	29	18	28	18	28	19	31	20
Launcher	m_T [Mg]	456	475	828	792	862	824	838	792	1166	1048
	l [m]	101	94	94	85	90	81	91	83	101	91
	d [m]	5.7	6.1	5.4	5.6	5.0	5.2	5.2	5.3	5.9	5.9

A target LEO orbit was defined with an assumed constant ascent velocity budget of $\Delta V_a = 9.85$ km/s. The first stage is assumed in a 9-engines configuration, while the upper stage employs a vacuum adapted engine. The values of the other parameters such as oxidizer-to-fuel ratios (O/F), specific impulses (I_{sp}), propellant storage temperatures (T_s) and expansion ratios are defined in Table 1. The structural efficiency of the different configurations was estimated using semi-empirical estimates combined with propellant tank sizing, and were calibrated with historical data for expendable stages. Other structural assumptions are an inter-stage of 6% of the first stage dry mass and a fairing mass comparable to that of the Falcon 9 vehicle. Tables 2 to 4 presents the resulting main characteristics for the different baseline launchers assessed in this study, designed for minimal launch effort assuming 15 reuses of the first stage[18]

3. Life Cycle Assessment Methodology

The Strathclyde Space Systems Database (SSSD) was used to calculate the environmental impact of each launcher configuration. The SSSD is a space-specific Life Cycle Sustainability Assessment (LCSA) database that can be used to determine life cycle environmental impacts of space systems. It was formed in openLCA using a process-based, attributional methodology which relies on physical activity data to develop a product tree derived from assessing all the known inputs of a particular process and calculating the direct impacts associated with the outputs of that process. Validated at ESA through a collaborative project in late 2018, the SSSD consists of >250 unique 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 A. R. Wilson.[20]

This was used to provide information for the following processes:

- Production of propellant
- Clean room fuelling
- Containment of propellant
- Decontamination and waste treatment of propellant
- General handling of propellant
- Storage of propellant
- Production of stage 1
- Production of stage 2
- Production of fairing
- Launch campaign
- Launch event
- Recovery operations
- Refurbishment of Stage 1

The analysis used three midpoint impact categories and a flow indicator which are considered as most relevant for quantifying the environmental impact of launchers. In terms of material impacts, Mineral & Metal Resource Depletion (MRDP) and the flow indicator Mass Disposed in Ocean (MDIO) were used. This latter flow indicator is measured in kg and is applicable for the total mass of launcher stages and fairing which end up in the ocean that are not systematically salvaged. As detailed atmosphere modelling was no possible within the scope of the study and is not readily available at early design phase, weighting factors were used for the atmospheric impact categories, which allows for a direct comparison with other life cycle phases. These are Global Warming Potential (GWP) over 100-year time horizon and

Table 5: Weighting factors per emission assumed in this study for global warming potentials over 100 years [kgCO_2eq/kgexhaust], and ozone depletion potential [kgCFC-11eq/kgexhaust]. Color scale indicate largest impact (red) to lowest impact (green) among propellant option

[CF/CF_ref]		H2O	CO2	CO	BC	Al2O3	NOx	ClOx	HOx
GWP 100Y	Ground	0.0005	1.0	1.57	460	1.23	8.5		
	Aviation	0.06	1.0	1.57	1116	1.23	114		
ODP					0.7	0.7	0.7	0.7	0.7

Table 6: Characterisation factors per propellant assumed in this study for global warming potentials over 100 years [kgCO_2eq/kgpropellant], and ozone depletion potential [kgCFC-11eq/kgpropellant]

Propellant	GWP 100								OD	
	Ground				Aviation (Reference)					
	All	No BC	CO2 Neutral	No BC and CO2 Neutral	All	No BC	CO2 Neutral	No BC and CO2 Neutral	All	No BC
hydrolox	0.00900	0.00900	0.00900	0.00900	0.17	0.17	0.17	0.17	0.014	0.014
methalox	2.48	0.64	1.94	0.10	5.24	0.78	4.70	0.23	0.017	0.014
kerolox	10.12	0.92	9.42	0.22	25.49	0.90	24.85	0.26	0.063	0.049
propalox	10.91	0.77	10.27	0.13	25.49	0.90	24.85	0.26	0.029	0.014
ammolox	0.00883	0.00883	0.00883	0.00883	0.15	0.15	0.15	0.15	0.014	0.014

Table 7: Average radiative forcing per mass of exhaust gas derived from.[7] CO forcing was assumed equal to CO_2 forcing

CO_2/CO	H_2O	Al_2O_3	BC
1.7×10^{-8} mW/(m$^2 \cdot$ Mg)	3.2×10^{-5} mW/(m$^2 \cdot$ Mg)	6.0×10^{-3} mW/(m$^2 \cdot$ Mg)	3.4×10^{-2} mW/(m$^2 \cdot$ Mg)

Ozone Depletion Potential (ODP) at steady state ozone change. However, it should be noted that this is considerable simplification highly dependent on the time horizon, location of the emission, associated lifetime, meteorological conditions, and other factors.[21] For example, HCFCs have a decreased ODP when released at ground level due to their earlier reaction in the troposphere, before they reach the stratosphere, and some compounds might have a high transient short term effect. In addition, only "indirect" impacts from exhaust species were accounted for which might underestimate total impacts, especially for stratospheric ozone depletion given the observed "ozone holes" in rocket trails. As no GWP and ODP factors are available for launch events, GWP values for a 100-year time horizon with kg CO_2eq for aviation[2] were assumed as the most analogous, although a sensitivity was performed in Section 4.2.1 with the ground based released GWP values reported by the IPCC[22] assumed in previous space industry LCA studies.[11,23] It should be noted that alternative climate metrics may be more representative, as a shorter time horizon of 20 years, or Averaged Temperature Response (ATR) or algorithmic environmental change functions.[24] Table 5 summarizes the values assumed for the different exhaust species for a ground and an aviation (reference) scenario Table 5. These were combined to synthesize various scenarios as presented in Table 6.

Nevertheless recent studies from The Aerospace Corporation[7] 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[6,14] analogous to aviation cirrus clouds, although these were not explored in this study due to its current high uncertainty lack of modelling capabilities. To highlight the potential underestimation, Radiative Forcing (RF) metrics (Table 7) were derived from the former study on high altitude emission by assuming them proportional with exhaust species. Nevertheless it should be noted that these could also vary significantly depending on the rocket type (propellant, trajectories, etc.), meteorological conditions and even launch frequency. Alternative metrics might be more suitable, analogous to the diverse options within the aircraft climate mitigation studies.[24] Similarly, ODP values for ground releases based were used based on the WMO model[25] using kg CFC-11 eq. as its reference. For NO_x, N_2O ODP values were assumed.

Lastly, MRDP is based on the CML (2001) model using kg Sb eq. units according to the reserve base horizon which refers to mineral and metal resources that have reasonable potential to become economically and technologically available. Each of the models used to represent each impact category are integrated as part of the SSSD and are based on the recommendations contained in the ESA LCA Handbook, which tailor the ISO 14040:2006 and 14044:2006 standards on LCA to be more space-specific.

3.1 Production and Refurbishment

For production, there are no difference between the different vehicles types due to a lack of inventory data. The inventory was mainly based on a literature review, with some data extrapolation for the manufacturing processes. Also, generic aluminium processes were used rather than aluminium alloys. Refurbishment operations were mainly based on the space shuttle orbiter and sized per kg., although it has to be noted that this might overestimate its impacts given differences between the vehicle types (The space shuttle orbiter was a complex upper stage designed for human spaceflight and capabilities to remain several days in orbit, requiring intense refurbishment after each flight) and recent progress to reduce operational efforts.

3.2 Recovery Operations

The impacts during stages transportation activities in the recovery operations consider typical direct emissions from a tug boat and supply vessel for the VTVL case, and from an aircraft for the VTHL case performing an IAC manoeuvre. 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.[26,27] Typical global averaged EI and GWP were then used for the vessels and aircraft.[2] It has to be noted that sulphur oxides (SO_x) emissions from shipping were excluded, even though it could result in a total global cooling from the sea recovery operations because of the current large emissivity index (≈ 200 times larger than that for aircrafts). This assumption was made because of the uncertainty in the indirect GWP values,[28] unknown proxy ships, and because of current worldwide efforts to reduce maritime SO_x emissions in the short term due it its harmful effects on humans and the ecosystem.[29] Their indirect emissions from their corresponding production, retro-fittings, refurbishment and other upstream activities were excluded, even though these could dominate if a low number of uses is expected, as seen for in their analogous cost estimates.

3.3 Launch Event Emissions

Emissions from launch vehicles during the launch event are a result from combustion exhaust compounds and plume reactions, from uncontrolled re-entry of material that burns in the upper atmosphere layers and from high thermal atmospheric chemical reactions occurring within induced hypersonic shock-waves.[14,31] Emissions deriving from exhaust of rocket engines can be divided in three families: Primary emissions, Secondary Emissions and emissions connected to Incomplete Combustion:

Figure 1: Soot formation in highly fuel-rich combustion reactions. Data extracted from Nickerson G. R. et al[30]

Figure 2: SpaceX's Merlin engine. On the right side of the thruster it is visible the exhaust from the gas generator fuel-rich combustion. Image Credit: Business Insider

Table 8: Emissivity Index [g exhaust/kg propellant]

Propellant	H2O	CO2	CO	BC	Al2O3	N2	NOx	ClOx	HOx
hydrolox	992.0						1.0	16.0	3.0
methalox	449.3	378.2	164.3	4.0			1.0	16.0	3.0
kerolox	287.8	451.2	254.7	20.0	50.0		1.0	16.0	3.0
propalox	354.0	417.4	221.1	22.0			1.0	16.0	3.0
ammolox	656.0					344.0	1.0	16.0	3.0

1. Primary emissions are the chemical species present at the exit of the nozzle. As they are required to predict the engine performance, the ideal reactions are well understood and emissions are predictable by commercially available software.

2. Secondary emissions are compounds formed outside the rocket engine due to chemical reactions in the high-temperature exhaust plume. Such compounds include, between others, Nitrogen oxides (NO_x) formed by reactions between the high-temperature exhaust products and the nitrogen (N_2) in the surrounding atmosphere; Hydrogen molecules (H and H_2) at the nozzle exit plane that react with oxygen molecules (O_2) from the surrounding air to form water vapor in the exhaust plume; and Carbon monoxide (CO) that at the nozzle exit plane is oxidized to carbon dioxide (CO_2) in the exhaust plume. The formation of the secondary emissions is strongly dependent on the altitude and local meteorological conditions.[32] Their impact might be significant, disturbing the higher atmosphere environment.[8]

3. Incomplete combustion emissions are, on the other hand, quite complicated to estimate and are often based on semi-empirical relationships. The most relevant of such emissions is doubtlessly Black Carbon (BC) (considered equivalent to soot) that, with a radiative force on the atmosphere various orders of magnitude bigger than CO_2, may cause a hard-to-neglect impact, as stated by numerous studies,[7,12] although it also include aluminium oxide particles ($Al_2O\ _3$) and other aerosols which may have a significant effect on stratospheric ozone. These compounds are also recognized to have an impact on human health.[33] Although it is possible to measure these emissions for terrestrial transportation,[34] such methodologies are not applicable to rockets, where the extreme temperature of the plume make it difficult to analyse. Despite the lack of real measurements, some attempts have been made to model BC as to quantify the engine performance with high detail, since it can cause progressive mechanical degradation or even contribute to some added thermal protection for the nozzle.[30] The later study covers the soot production in gas generator, very fuel-rich, applications for many propellants combinations: liquid oxygen with RP-1 (Kerosene), Methane and Propane. Results as a function of mixture ratio are provided in Figure 1. Although it is not possible to extrapolate to main engines, where combustion is close to stoichiometric ratio, it gives a good estimation of soot produced in open-cycle, gas generator engines, currently the most utilized ones, such as the SpaceX's Merlin engine shown in Figure 2. In such engines, usually 2-4% of the total fuel consumption is used to drive the turbine in a fuel-rich pre-burner.[35]

Table 8 shows the estimated emissions for the various propellants utilized based on the first stage O/F and expansion area ratio of 30. The assumed reference values for soot emissions are also provided, with the soot EI for RP-1 based on M. N. Ross et al[7] and as estimated from Atlas II High spatial resolution imagery,[36] although it could be considered an underestimate given observations of up to 3% in mass fractions.[37] The value for propane was based on the relative peak difference with RP-1 observed in Figure 1, and for methane based on an 80% reduction similarly to what was reported by the National Academies of Sciences, Engineering, and Medicine.[32]

In addition to rocket exhaust products, emissions are also produced from the demise of upper stages during uncontrolled re-entries and even from high speed shockwaves. For uncontrolled reentries, current research is mainly focused on casualty risk, such as fraction of debris that can survive and reach ground and may become a direct danger. However, it is clear that if the total mass of material released from defunct satellites or upper stages that burn in the atmosphere continue its steady increase, it could have an effect on its composition.[38,39] A few projects, sponsored by ESA Clean-Space initiative, estimated that the current impact on toxicity and climate, even in the worst cases scenario, have a marginal and local effects. Two projects[4041] independently evaluated the RF and Ozone depletion deriving from uncontrolled re-entry up to year 2100, concluding that the effect of global temperature would be less than 96×10^{-9} K, and Ozone loss less than 8×10^{-4} K impacts many orders of magnitude lower than other common human activities. In this study, a preliminary analysis was preformed to assess its possible significance in Section 4.2.2 assuming survivability rates of 35% of the entry mass, and from those, 80% being Al which would later oxidize into Al_2O^3. Although it was not included in the nominal assessment, the high potential impacts identified require a dedicated

Table 9: Environmental impact results for the VTVL RTLS case. Color scale indicate largest impact (red) to lowest impact (green) among propellant options

Propellant	GWP [GgCO2 eq]							OD [MgCFC-11eq]		MRDP [MgSbeq]		MDIO [Mg]	
	Launch	Total			Prem.			Total	Prem.	Total	BE	Total	BE
	Event	5 R	10 R	15 R	5 R	10 R	15 R	15 R	15 R	15 R	reuses	15 R	reuses
hydrolox	.07	19.12	18.79	18.69	6.8%	4.9%	4.3%	7.2	25.3%	1.72	3 R	11.75	2 R
methalox	3.96	24.81	24.39	24.25	10.6%	8.8%	8.2%	14.4	28.2%	2.05	3 R	13.71	2 R
kerolox	18.97	40.36	39.95	39.81	16.1%	14.9%	14.5%	52.8	26.2%	2.00	3 R	13.39	2 R
propalox	19.96	40.14	39.73	39.59	16.4%	15.2%	14.8%	24.7	27.8%	2.06	3 R	13.76	2 R
ammolox	.16	24.13	23.56	23.37	11.1%	8.5%	7.6%	17.	34.1%	2.51	3 R	16.55	2 R

Table 10: Environmental impact results for the VTVL DRL case. Color scale indicate largest impact (red) to lowest impact (green) among propellant options

Propellant	GWP [GgCO2 eq]							OD [MgCFC-11eq]		MRDP [MgSbeq]		MDIO [Mg]	
	Launch	Total			Prem.			Total	Prem.	Total	BE	Total	BE
	Event	5 R	10 R	15 R	5 R	10 R	15 R	15 R	15 R	15 R	reuses	15 R	reuses
hydrolox	.07	18.97	18.62	18.5	5.9%	4.0%	3.3%	6.8	18.2%	1.41	2 R	11.75	2 R
methalox	3.81	24.29	23.86	23.71	8.3%	6.4%	5.8%	13.6	21.1%	1.71	2 R	13.71	2 R
kerolox	18.43	39.55	39.11	38.97	13.7%	12.5%	12.1%	51.	21.9%	1.67	2 R	13.39	2 R
propalox	19.06	38.79	38.36	38.22	12.5%	11.3%	10.9%	23.4	20.7%	1.70	2 R	13.76	2 R
ammolox	.16	23.5	22.92	22.73	8.2%	5.6%	4.7%	15.9	25.4%	2.14	2 R	16.55	2 R

Table 11: Environmental impact results for the VTHL DRL case. Color scale indicate largest impact (red) to lowest impact (green) among propellant options

Propellant	GWP [GgCO2 eq]							OD [MgCFC-11eq]		MRDP [MgSbeq]		MDIO [Mg]	
	Launch	Total			Prem.			Total	Prem.	Total	BE	Total	BE
	Event	5 R	10 R	15 R	5 R	10 R	15 R	15 R	15 R	15 R	reuses	15 R	reuses
hydrolox	.07	19.74	19.22	19.04	10.2%	7.3%	6.3%	6.6	15.7%	1.48	3 R	12.67	3 R
methalox	3.63	24.54	23.91	23.7	9.4%	6.6%	5.7%	12.8	14.3%	1.61	3 R	13.41	3 R
kerolox	17.01	38.05	37.45	37.25	9.4%	7.7%	7.1%	47.	12.4%	1.58	3 R	13.22	3 R
propalox	17.74	37.62	37.03	36.83	9.1%	7.4%	6.8%	21.7	12.1%	1.63	3 R	13.66	3 R
ammolox	.14	23.28	22.51	22.25	7.2%	3.6%	2.4%	14.4	13.8%	2.01	3 R	16.20	3 R

analysis. The last source of pollutants in the high atmosphere is connected to re-entry shockwaves. The high thermal energies encountered in high speed reentry for both uncontrolled and controlled events lead to vibrational excitation of oxygen and nitrogen molecules that causes their dissociation and production of significant amounts of nitrogen oxides as a consequence of the disrupted equilibrium.[31] In the case of high launch rates, these emissions could exceed natural meteoric production significantly.[14] This family of emissions was studied in the past, observing that a high dependency on the flight profile, entry angles and vehicle area exists, that lead to a production of approximately 17.5 ± 5.3% of the mass of the space shuttle orbiter during its re-entry.[31] The emissions occurred mostly at an altitude between 55-90 km at speeds higher than 4 km/s. Given its possible predominant ozone depletion[14] and climate forcing,[42] it was assumed that all upper stages and fairings reentering/demising would generate approximately the same amount of nitrogen oxides per dry mass as the space shuttle. For first stages this was neglected, as they typically enter at lower speeds, gaining kinetic energy at lower atmospheric altitudes than the space shuttle, where vibrations excitation and dissociation onset was delayed by higher pressures.[43] Nevertheless, given its 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.

4. Environmental Assessment of RLVs

The proxy launch vehicles using the different technologies 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 sensitivity assessment in Section 4.2, a discussion of significance of future emissions Section 4.3 and a summary of its limitations in Section 4.4.

4.1 Life Cycle Assessment

The life cycle environmental impacts from the different launches assessed differ in some key phases. Tables 9 to 11 provide results for the different impact categories and technologies. These are discussed individually in the following sections.

4.1.1 Material Resource Depletion and Mass Disposed in Ocean

One of the main sustainable traits of re-usability can be seen through the recycling of the first stage for additional launches which may still compensate with the additional resources required for spare parts and maintenance operations. This can be seen through an early break-even of 2-3 launches with respect to the equivalent expendable vehicle, although no spare components were assumed. In terms of mass disposed in ocean, a similar early break-even can be observed. Nevertheless, it it was assumed that the launchers were all made from a similar material. Re-usability might actually introduce the need for the use of critical materials as for TPS design and to enhance the service life of critical components as the engine. Therefore this assessment should be improved in the future with a more detailed mass breakdowns.

4.1.2 Global Warming Potential

GWP values showed that hydrocarbon launch vehicles had significantly increased impacts when compared to ammonia launches even though they were lighter. The hydrogen fuelled launch vehicles attained the lowest impacts even when accounting for its fossil fuel based production and relatively energy intensive handling requirements.

Nevertheless, for all propellant combinations, GWP increased significantly with respect to the expendable launch vehicles, as it can also be seen in Figure 3 showing the impacts as a function of number of reuses of the first stage, which is not able to reach a break-even point for reusability. This might be explained by increased propellant requirements and corresponding larger emission impacts, especially for hydrocarbons, and impacts from propellant production, handling and storage.

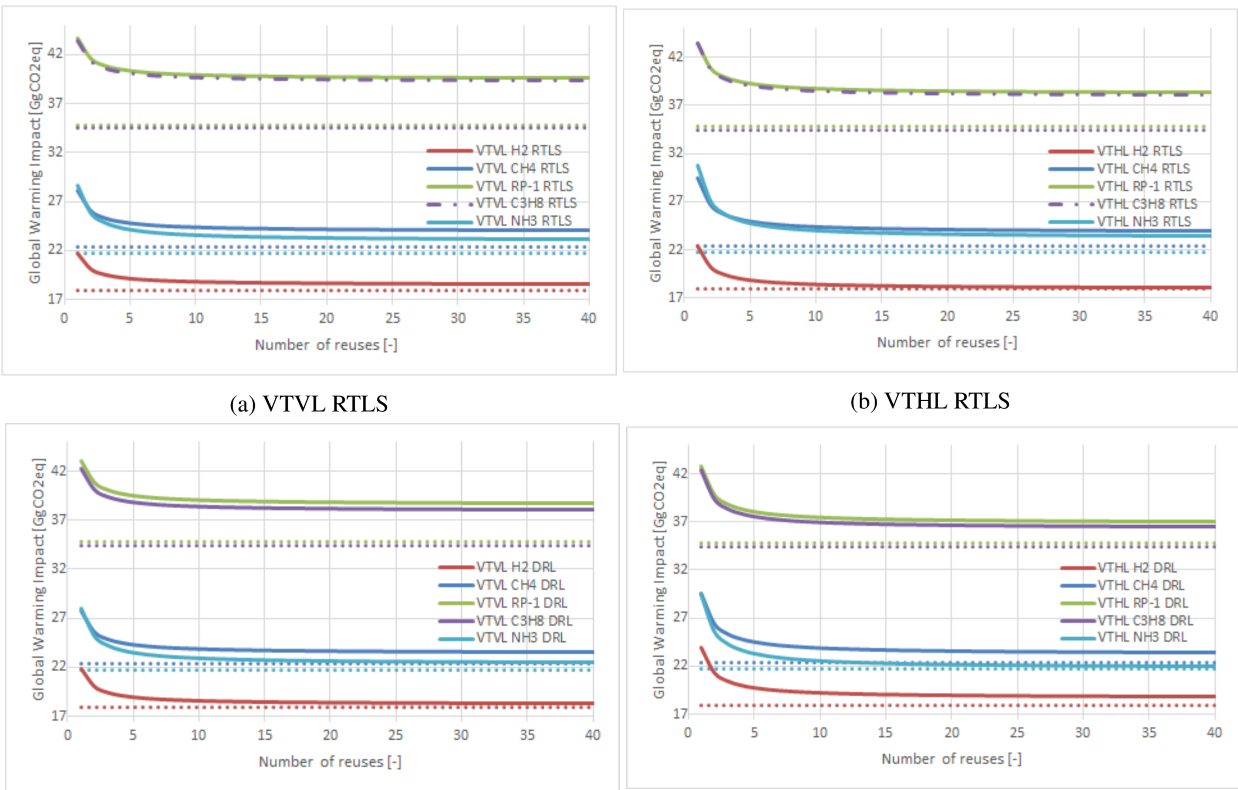


Figure 3: Averaged global warming impacts per launch as a function of number of reuses for different propellant combinations. Dotted lines represent equivalent expendable launchers

The increased influence from propellant storage is especially noticeable for the hydrogen vehicle Figure 4, which is nevertheless reduced for the ammonia launcher as shown in Figure 5 because of its lower O/F and less energy intensive ammonia storage. On the other hand, impact from decontamination and waste treatment dominates for the ammonia fuelled launcher resulting from its lower payload efficiency requiring higher propellant amounts. These phases was already identified by T. Maury et al as a potential hotspot.[44] In addition, the launch event showed the least impacts for both options, which might indicate a large potential for mitigation by reducing the carbon intensity from propellant storage and handling through low carbon energy sourcing, and from using higher O/F ratios for hydrogen, and possibly lower O/F ratios for ammonia as long as the propulsion efficiency of the later is not compromised significantly. Deviations from stochiometric O/F ratios may also lead to added radical emissions and products from

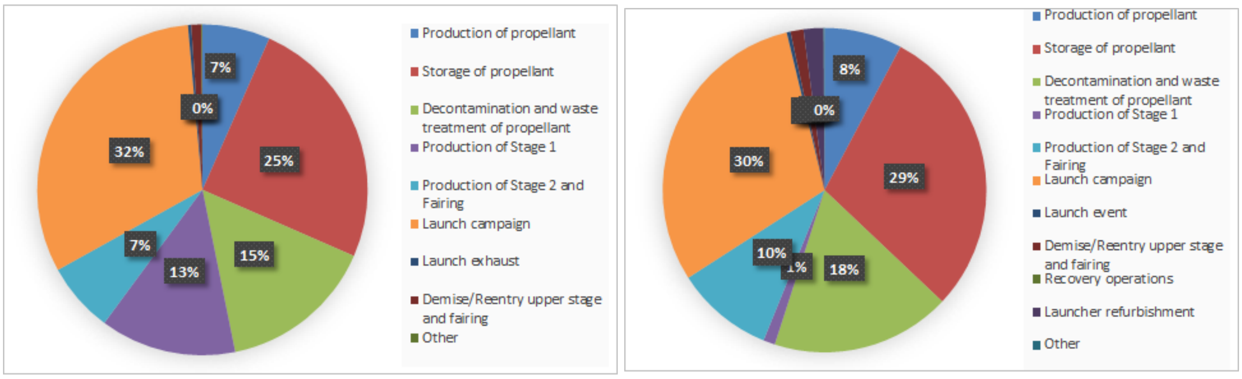


Figure 4: Share of global warming impacts for hydrogen based ELV (left) and for VTVL RTLS with 15 reuses (right)

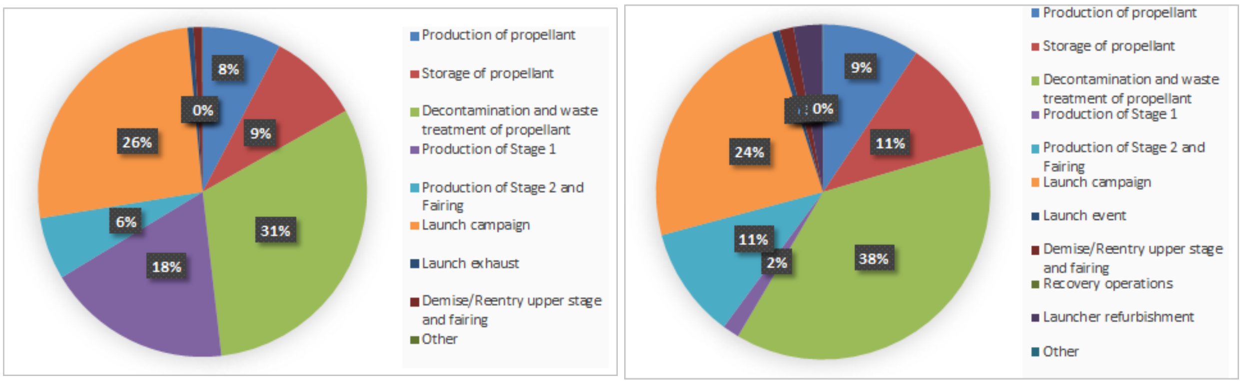


Figure 5: Share of global warming impacts for ammonia based ELV (left) and for VTVL RTLS with 15 reuses (right)

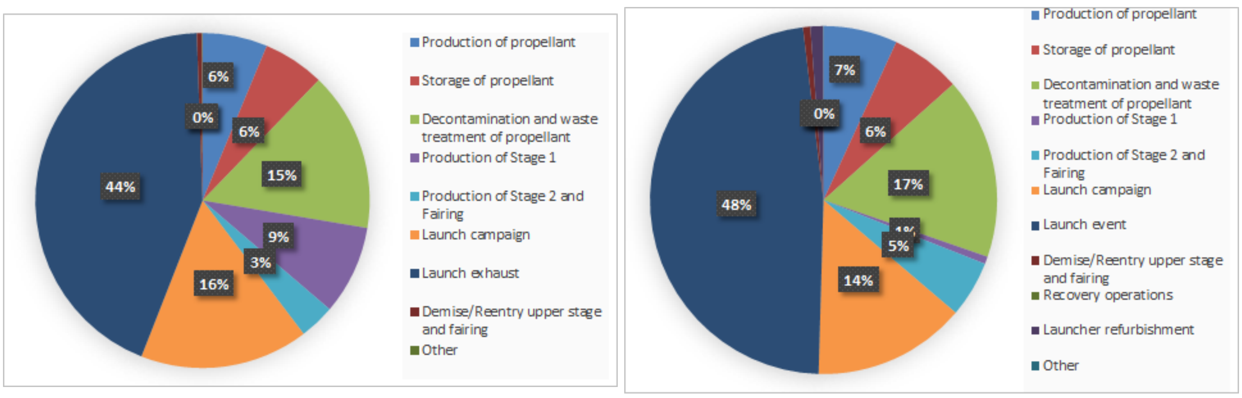


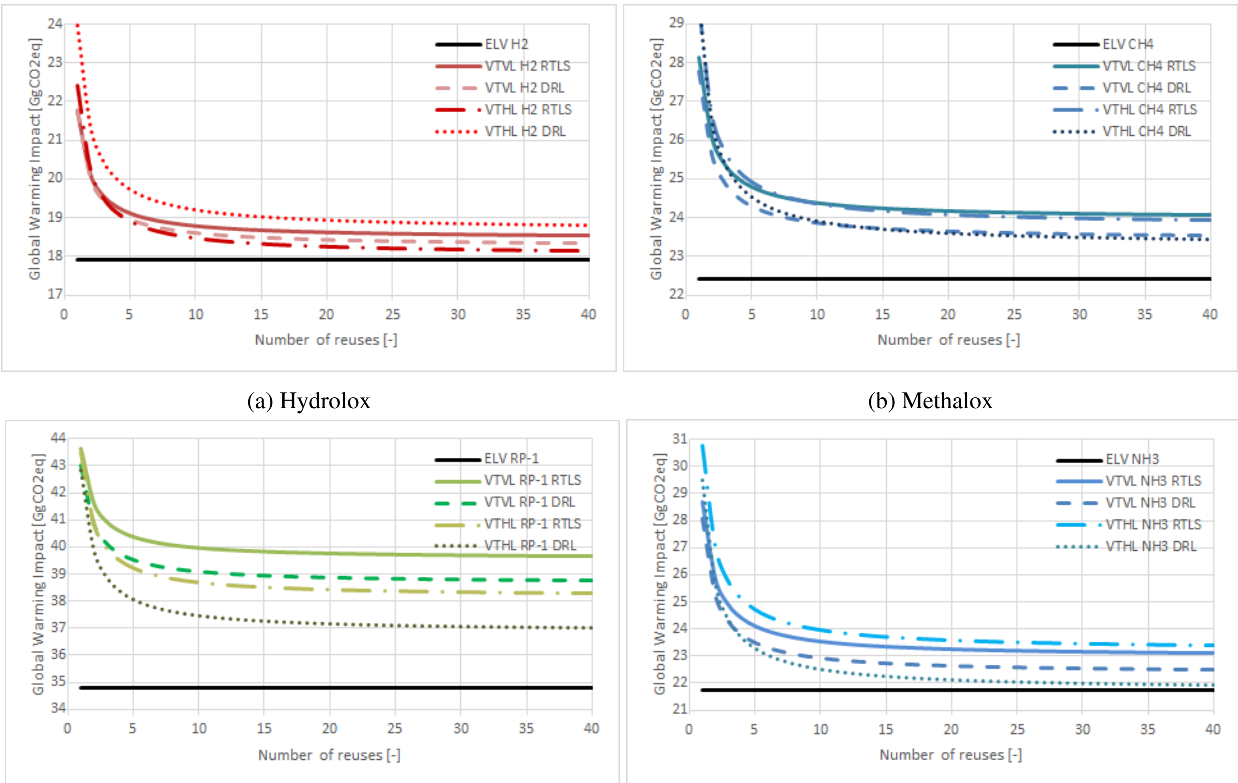
Figure 6: Share of global warming impacts for kerosene based ELV (left) and for VTVL RTLS with 15 reuses (right)

incomplete combustion, further increasing launch events impacts.

For the hydrocarbon stages, the increase with respect to the equivalent fully expendable vehicle is much more pronounced as a consequence of larger propellant requirements and share of launch event impacts, as seen also in Figure 6 for the VTVL RTLS kerosene fuelled with a total of 48% of the total life cycle impacts for 15 reuses. This is a consequence from the higher soot content in the exhaust, which can be up to 2% of the exhaust mass for kerosene and cause a 10× increase in the launch event GWP impact using the values reported in Table 6. For the methane stages, even if it was assumed to have a lower soot contents, it was seen that it was not possible to surpass ammonia even when considering the larger propellant requirements and energy intensive handling processes for the later.

A comparison in terms of the different recovery options for all propellants is shown in Figure 7. It is seen how vehicles performing DRL recoveries attained the least GWP. This was especially true for the VTHL with the In-Air-Capture method, which might still be more sustainable even when accounting for the jet fuel based aircraft operations. Nevertheless, this might not be the case of a solely cost efficiency driven design strategy, as it is seen for the hydrogen fuelled stage with the highest impact for the VTHL DRL option. This was a result from the larger propellant requirements from its higher staging value than that indicated by minimum mass driven design,[18] explained by its relatively higher robustness against staging compared to the other technologies, lack of propulsive recovery manoeuvres penalized by larger separation speeds, and higher production costs per mass of its hydrogen fuelled upper stage.

Finally, the significance of the high GWP figures should be highlighted in terms of its potential financial externalities. The European Emissions Trading System (ETS), currently applicable to energy, aviation and production of some resources, reached 100€/Mg$CO_{2,eq}$ in February 2022, and forecasts predict a considerable rise in the upcoming years. The launch vehicle industry is currently excluded, but there are near term plans to increase the ETS scope. At GWP impacts per launch in the order of 10Gg, and assuming an allowance price of 100€/Mg$CO_{2,eq}$, internalized costs from global warming regulations alone could reach 1M€. Given the higher GWP impacts for methalox VTVL ≈ 24Gg, the possible increase by a factor of 5 considering Starship's payload capacity, it might be that emissions allowance costs alone might surpass estimated Starship's launch price in the order of 10M$.[45] This highlights the need to consider near term regulatory concerns early in the design of launch vehicles as it may alter the business case significantly.[46]



(a) Hydrolox

(b) Methalox

(c) Kerolox

(d) Ammolox

Figure 7: Averaged global warming impacts per launch as a function of number of reuses for different recovery strategies

4.1.3 Stratospheric Ozone Depletion Potential

In terms of stratospheric ozone depletion, significantly higher values were observed when employing reusability for all propellant options as seen in Figure 8 as a consequence of the almost exclusive launch event (and reentry NO_x) share

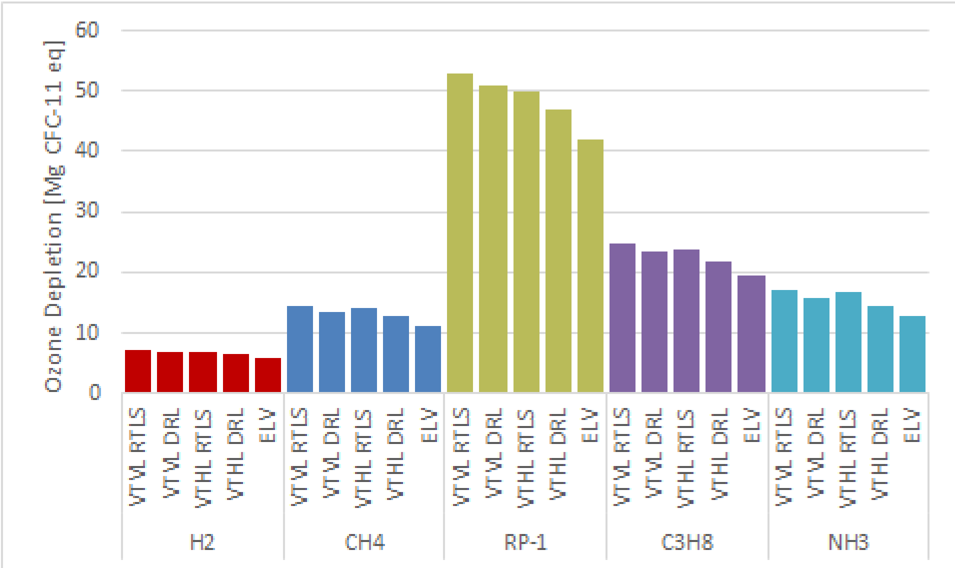
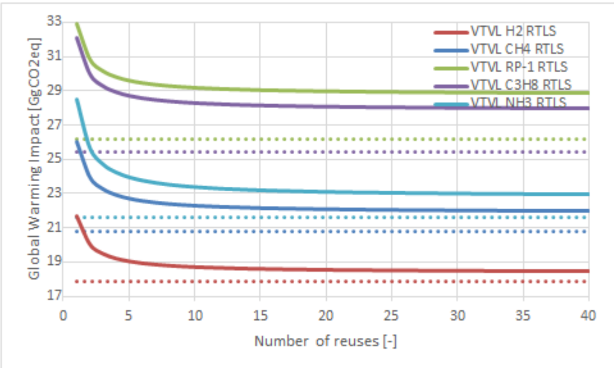
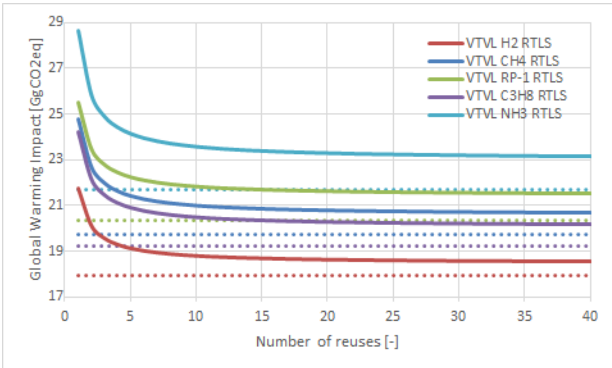


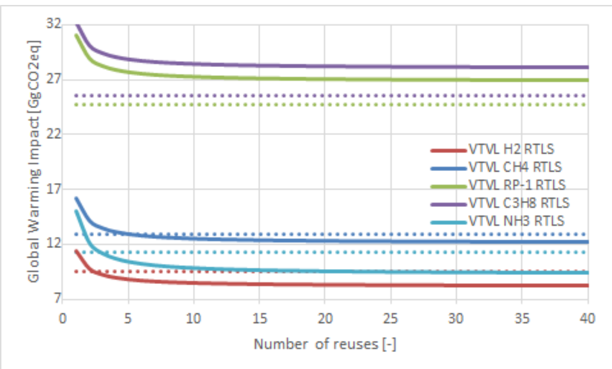
Figure 8: Averaged stratospheric ozone depletion impact per launch for 15 reuses in the RLV cases



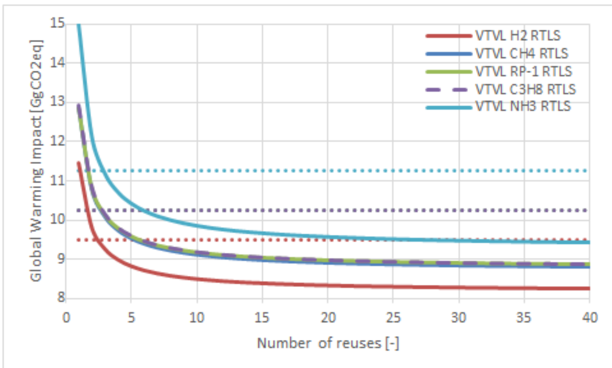
(a) Life-cycle GWP with launch event emissions characterized with ground based factors



(b) No soot emissions



(c) Fully carbon neutral propellant production



(d) Fully carbon neutral propellant production and no soot emissions

Figure 9: Sensitivity analysis of averaged global warming impacts per launch as a function of number of reuses for the VTVL RTLS case. Dotted lines represent equivalent expendable launchers.

Table 12: Averaged radiative forcing per propellant combinations. Color scale indicate largest impact (red) to lowest impact (green) among propellant options

Propellant	Ratio of total Radiative Forcing			Total Radiative Forcing	Annual Launchers	RLV Premium
	CO/CO2	H2O	BC			
hydrolox	0.0E+00	1.0E+00	0.0E+00	0.012 mW/m²	0.1%	18.6%
methalox	6.1E-05	9.4E-02	9.1E-01	0.110 mW/m²	0.8%	20.7%
kerolox	1.7E-05	1.3E-02	9.9E-01	0.537 mW/m²	3.9%	19.5%
propalox	1.4E-05	1.5E-02	9.9E-01	0.568 mW/m²	4.1%	19.5%
ammolox	0.0E+00	1.0E+00	0.0E+00	0.021 mW/m²	0.2%	23.6%

of emissions. This was nevertheless reduced significantly for hydrogen stages, with ammonia and methane performing similarly, the later one as a consequence of its inefficiency and large water emissions and assumed ClO_x emissions. Kerosene vehicles showed significantly higher ODP, 7× higher than hydrogen vehicles from a combination of its BC and Al_2O_3 emissions. A larger dependency was nevertheless observed in terms of recovery strategies, with the VTHL DRL vehicles having a slightly lower increase in ODP $12-16\%$ compared to $18-34\%$ for VTVL launchers.

4.2 Sensitivity Assessment

In Section 3 it was discussed that large uncertainty in key aspects of LCA remain. This section performs a preliminary sensitivity analysis to explore its issues and identifies potential areas of improvement. Figure 9 shows GDP impacts for various scenarios assessed which are further described in the upcoming subsections.

4.2.1 Emission Profile Effects in Climate Forcing

The LCA from the previous section assumed simplified characterisation factors for the different exhaust products and neglected differences in the emission profiles and their impacts at various atmospheric layers. Nevertheless, impacts from emissions vary significantly with altitude and even geographical regions as discussed in Section 3.3. To illustrate this problem, a sensitivity to the GWP assumed and RF factors from[7] was performed.

For GWP, because of the lack of representative values for launchers, values for aviation were assumed as reference. Figure 9a shows the results for VTVL RTLS case when using ground based GWP as used in previous studies. When compared to Figure 3a, it can be seen how ground based values can indicate a GWP 9% lower for methane fuelled vehicles reused 15 times, and up to 30% lower for kerosene and propane stages as a consequence of the larger impact of BC and NO_x emissions. Nevertheless, as noted by[7] and,[14] launch vehicles perform considerably different flight profiles and therefore these weighting factors might not be fully representative.

To highlight this uncertainty in the models used, a separate preliminary assessment assessed averaged radiative forcing provided in Table 7. A comparison can be seen in Table 12. The analysis shows how the impact of BC emissions dominate by several order of magnitude the impact from CO_2, followed by water emissions. This stresses how hydrocarbon technologies, especially through the use of RP1 and propane, could have significant higher radiative forcings. It is also seen how radiative forcing increases for all technologies by a similar $20-23\%$.

BC emissions from Methane and propane fuelled stages are nevertheless highly uncertain based on different values reported in the literature. The values used as reference assumed a possible worse case scenario with a 80% reduction figure from a study by the National Academies of Sciences, Engineering, and Medicine.[32] Nevertheless, if values of 96% reduction in BC as observed in a study on rocket turbo-pumps emissions[30] are used, RF of methane would only be slightly larger than that from hydrolox (×2.4) and ammolox (+43%) technologies. If no black carbon emissions are assumed, it is seen how methalox technology could achieve the lowest RF as a consequence of its reduced water emissions. Similarly, propane could achieve even higher reductions in soot if no black carbon emission, although results on rocket turbo-pumps suggest similar soot production as from kerosene engines.[30]

4.2.2 High Speed Flight and Demise of Expendable Components

Give the importance of the NO_x emissions emitted during ascent and reentry high speed flight identify by,[14] a close assessment is presented. In addition, the demise of expendable stages might also increase the amount of heavy metals

Table 13: Comparison of environmental impacts during launch events from exhaust gasses, NO_x production in shockwaves from upper stage and fairing reentries, and hypothetical proxy Al_2O_3 emissions from demise of upper stage and fairing for the VTVL RTLS case. Color scale indicate largest impact (red) to lowest impact (green) among phases

Propellant	GWP			ODP		
	Exhaust	Reentry NOx	Demise Al2O3	Exhaust	Reentry NOx	Demise Al2O3
hydrolox	22%	76%	2%	49%	13%	38%
methalox	93%	6%	0%	66%	9%	26%
kerolox	99%	1%	0%	89%	3%	9%
propalox	99%	1%	0%	77%	6%	17%
ammolox	34%	64%	2%	66%	9%	25%

and pollutants in the upper atmosphere which may have climate effects. A preliminary assessment of its significance was carried out by assuming that 65% of the expendable upper stages and fairings were demised during reentry, and 80% of that amount was Al which would later oxidize to Al_2O_3. Results for these later possible impacts and those from the rocket exhaust products and reentry NO_x are shown in Table 13.

Table 13 show large impacts from reentry NO_x emissions in GWP for hydrolox and ammolox launchers (assuming aviation based CF). Nevertheless the share was lower for hydrocarbon based launchers as a consequence of the higher total impact caused by additional pollutants. Similar trends were observed in terms of ODP. In this later one, the results for hydrolox and ammolox propellants indicate that exhausts impacts dominates. An emission breakdown shows a contribution to ODP from ClOx produced of 80%. However, the total ODP from various radicals was originally estimated based on results from detailed atmospheric simulations and their results distributed equally per radical category. Although hydrogen/ammonia might result in a lower emissions of chlorine radicals, the increase from other radical is a possibility. The distinction between the various radicals per propellant choice was not attempted, but should be addressed in the future.

For GWP, it is seen how the impacts from alumina particles might be negligible. Nevertheless, using the RF values from Table 7 would lead to an increase of 98% of the radiative forcing values from hydrogen rockets launches derived in Table 12. This highlights a possible large discrepancy resulting from the assumed emission profile which requires further assessments.

4.2.3 Carbon Neutral Propellant

Carbon neutral hydrocarbon fuels can compensate the CO_2 emitted during exhaust by capturing a similar amount from the atmosphere while being produced. These have been considered by several organizations to mitigate the impact from launch vehicles[a][b]. Various options exists, as using bio-fuels derived from waste products, wood, and agriculture, or produced synthetically from CO_2 as with Direct Air Capture (DAC).[47] Nevertheless, they present large challenges, as excessive land use for biofuels,[48] and increased energetic and material requirements.[49] As a consequence, their large scale use for rocket propellants may interfere with other sectors in the upcoming decades.[50]

Nevertheless, in this assessment an ideal case of fully carbon neutral propellant production was assumed, with the corresponding omission of CO_2 from the launch event for hydrocarbon fuels. In addition, the climate impacts from handling, storage, and decontamination and waste treatment were neglected. As a result, the only remaining contributors to climate change were the non-CO_2 emissions from the launch event, those from launch campaign activities, and emissions during production and refurbishment of stages.

Figure 9c, for the VTVL RTLS case, and Table 14, for the VTHL DRL case show how GWP could be reduced. Large mitigation values were observed in Figure 9c, where hydrogen, ammonia and methane fuelled stages were able to attain break-even points in reusability in less than 15 launches. This is mostly attained through emission free storage, decontamination and waste treatment processes, as seen from the large percentage reductions in total impacts for hydrogen and ammonia fuels in Table 14. For the launch event, the GWP was only reduced by 10% for carbon neutral methane, and by 2 – 3% for carbon neutral kerosene and propane as a consequence of their assumed high soot content. Figure 9d shows GWP as a function of reuses if soot production is also neglected. It can be seen how in this case reusability compensates for all propellant types, and hydrocarbon fuels perform similarly but still with a slight

[a] "Musk Wants SpaceX to Turn CO_2 From Atmosphere Into Rocket Fuel", Energy Connects, Dec. 31, 2021. https://www.energyconnects.com/news/renewables/2021/december/musk-wants-spacex-to-turn-co2-from-atmosphere-into-rocket-fuel/ [accessed Apr. 15, 2022].

[b] "Orbex set to launch world's most environmentally friendly space rocket",Orbex Press Releases, 21 October 2021, https://orbex.space/news/orbex-set-to-launch-worlds-most-environmentally-friendly-space-rocket [accessed June. 19, 2022]

Table 14: Differences in global warming impact from hypothetical fully carbon neutral propellant production and emission free propellant processing for the VTHL DRL case. Color scale indicate least reduction (red) to highest reduction (green) among propellant options. BE stands for break-even

Propellant	Launch Event	Total			BE reuses
		5 R	10 R	15 R	
hydrolox	0.0%	-50%	-51%	-52%	8
methalox	-10.4%	-44%	-46%	-46%	12
kerolox	-3.0%	-30%	-30%	-30%	
propalox	-2.5%	-27%	-27%	-27%	
ammolox	0.0%	-51%	-53%	-53%	6

higher impact than using hydrogen as fuel. The ammonia fulled launcher showed the higher impact resulting from its larger vehicle mass and H_2O and NO_x emissions.

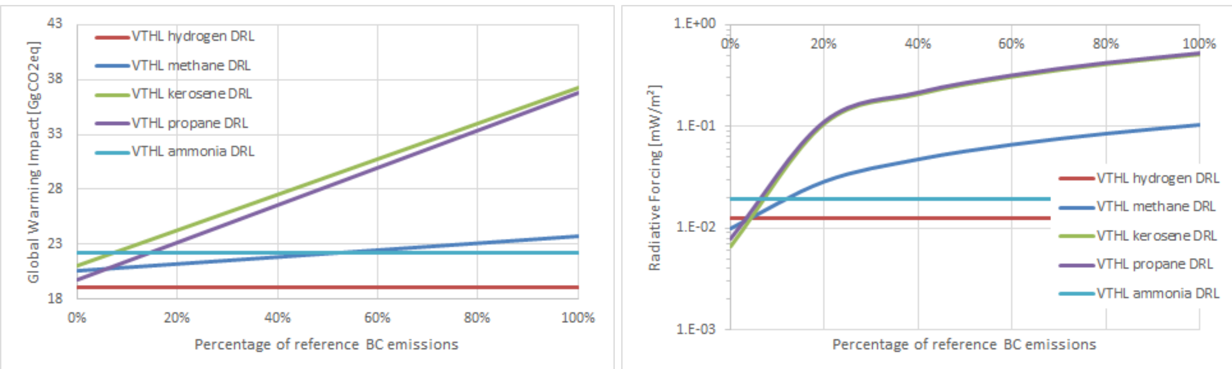
4.2.4 Soot Emissions

It was seen in previous sections how soot emissions dominate the launch impacts of hydrocarbon fuelled rockets making them less attractive compared to ammonia and hydrogen alternatives, even in cases where propellant production could be made carbon neutral. Nevertheless high uncertainty remains in both the possible emission indexes, climate forcing and ozone depletion potential from soot alone as discussed in Section 3.3. As a consequence, a sensitivity with the EI by applying reduction factors from the references values in Table 8 was completed and shown in Figure 10 for 15 first stage reuses of the VTHL DRL vehicle in terms of the various climate forcing metrics.

It is seen how attractive reductions with respect to the ammonia and hydrogen alternatives are only attained with significant reductions in BC of around 90% with respect to their corresponding references, with even larger reductions obtained when considering RF as the climate forcing metric. Such ambitious reductions in soot EI may seem unreachable for most hydrocarbon fuels, especially when high temperature non-stochiometric reactions are involved in typically fuel rich turbo-pumps, combustion chambers and plume afterburning.

4.3 Atmospheric impacts from future launch fleets

A final preliminary assessment was conducted to assess the significance of the atmospheric environmental impacts assessed in the previous sections for the different propellant types. It considered annual launch rates of up to 10^6 representing possible future efforts for making Space Based Solar Power (SBSP),[51] Earth-to-Earth rocket transport and human migrations to the Moon or Mars.[50] These high launch rates are also required for, and would be enabled by, the economics of reusable vehicles with high number of reuses. The minimal launch rates for SBSP assumed launches with the Skylon vehicle, with a lower payload capacity, and therefore equivalent launch rates using the launchers analysed might be lower. For Mars missions, the number of launches were multiplied by a factor of 5, representing lower



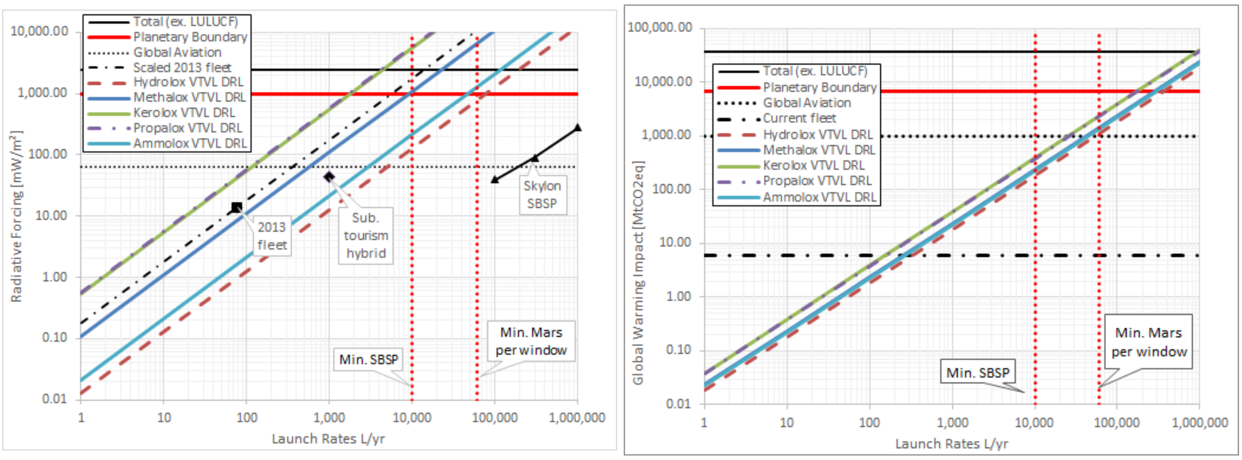
(a) Equivalent CO_2 emissions for VTHL DRL case with 15 first stage reuses as a function of soot reduction

(b) Radiative Forcing for VTHL DRL case with 15 first stage reuses as a function of soot reduction

Figure 10: Sensitivity to black carbon emissions for VTHL launchers optimized for DRL and 15 reuses in terms of Global Warming Impact (left) and Radiative Forcing (right)

payload capacity compared to the Starship vehicle.[50] GWP values from the current launch industry including satellite manufacturing and development phases are reported by A. R. Wilson et al,[52] while the launch event radiative forcing and hypothetical impact from a fleet of hybrid powered suborbital launches were estimated by M. N. Ross et al.[7] No cross interactions nor geospatial effects were assumed from localised atmospheric exhaust accumulation. Figure 11 show estimated climate forcing impacts and Figure 12 stratospheric ozone.

It is seen how current atmospheric impacts from the launch industry remain small when compared to reported impacts from all anthropogenic emissions[22] and planetary boundaries.[53] Nevertheless, it should be noted that the representation in GWP might not be adequate for launch emissions. In fact, a full replacement of current launch rates with the kerosene and propane based launchers assessed in this study could lead to radiative forcing values similar to global aviation,[7] a sector already under regulatory pressure to reduce its impacts. In terms of future launch rates, as those estimated for suborbital tourism, space based solar power and mars exploration, it is seen how atmospheric impacts could exceed planetary boundaries earlier by hydrocarbon based stages, being especially noticeable in terms of radiative forcing and stratospheric ozone depletion. It should be noted that for the higher launch rates of $10^5 - 10^6$, up to 1-10 Tg of BC might be deposited annually in the stratosphere. For this high level of emissions, the climatic response might actually switch to a net surface cooling, as seen with atmospheric simulations for a similar material amount albeit injected at a faster rate,[54] and may also interfere with global climatic patterns.[55] The impacts for hydrolox technology in terms of radiative forcing were also seen to exceed those estimated with state of art atmospheric models for a fleet of combined air-breathing/rocket spaceplanes for SBSP deployment,[14] which may result from the lower efficiency of full rocket based propulsion, increased target payload to LEO, a possible overestimation, and high modelling uncertainty. The estimated stratospheric ozone depletion may also exceed planetary boundaries for SBSP deployment and Mars missions even for the least polluting hydrogen fuelled launcher. These results highlight previous findings that there are



(a) Launch rates vs. RF (b) Launch rates vs. GWP

Figure 11: Estimated future climate change impact metrics for VTVL DRL launchers in RF (left) and GWP (right)

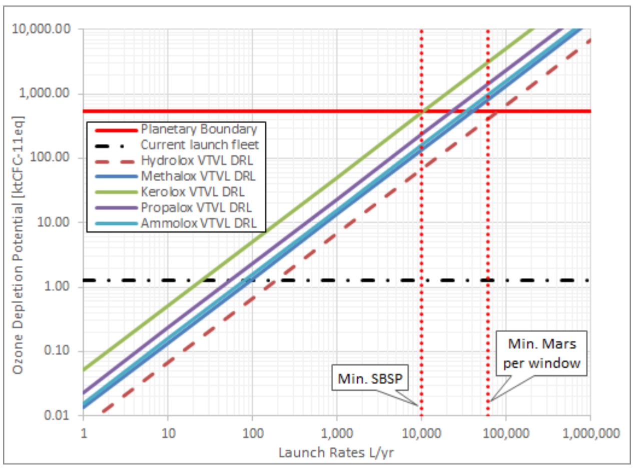


Figure 12: Estimated future stratospheric ozone depletion potential for VTVL DRL launchers

certain environmental limits with current rocket based technology constraining launch sector growth.[1,50]

Given the estimated high impact for kerosene based VTVL launchers, the current surge of Falcon 9 launches may be of a concern. Nonetheless, it should be noted that the kerosene based VTVL DRL hydrocarbon stage is not an analogy of the Falcon 9 vehicle, as it was designed for payloads to LEO in RLV mode approximately 80% larger, with associated larger emissions, although can be analogous to Falcon Heavy launches.

4.4 Limitations

High uncertainties remain in key parts of the life cycle assessment which still limits the potential for eco-design and might indicate certain environmental limits of future space activities:

- Weighting factors have not be calculated according to launch event emission profiles and state of art atmospheric models. Impacts from various emissions, and the emissivity index themselves, may differ significantly in each atmospheric layer and flight regime, and also can depend significantly on the time horizon used. BC, Al_2O_3, water vapour and radical emissions all had to be weighted according to literature and expert input, due to vast uncertainties, and cloud formation impact was not assessed. These may have significant effects on the trade off assessment of the different technologies (Section 4.2). Alternative ozone depletion and climate forcing metrics may provide different significance.
- Medium-to-High uncertainty remains on exhaust of different species. It was assumed that all fuel was burned, while in reality some might be left which may affect GWP and ODP, as was seen with H_2 emissions affecting stratospheric ozone.[14] BC emissions from methane stages are also uncertain and may affect relative comparisons as seen in Section 4.2.4. The dependency of emissions from radicals and their associated ODP/GWP are also uncertain on propellant choice was also not addressed. Reentry NO_x production was assumed proportional to that of the Space Shuttle Orbiter, and might therefore vary significantly for expendable stages, fairings and high speed main stages depending on their flight profile, ballistic coefficient and aerodynamic capabilities.
- The SSSD lacked datasets on ammonia and propane production, so Ecoinvent was used exclusively. Furthermore, the impacts of propellant leakages and purging throughout their life cyle was not assessed. These could affect GWP and ODP impacts for methane and hydrogen fuels from their production, handling and onsite storage.[56–58] Refurbishment operations were based on the Space Shuttle which might not be representative of modern operations.
- Horizon used for mineral and metal resource depletion is not those recommended by the European Commission,[59] but rather those recommended by the ESA LCA guidelines.[60]
- The assessment assumed the launchers were mostly made of aluminium. This assumption should be revised in the future as reusability might require critical materials, and it might differ between propellant choices.

5. Conclusion and Recommendations

The study conducted a first order assessment of various design options for future launchers in terms of reusability, recovery strategies and propellant choices. The results indicate that mitigation might require balancing between different impact categories and other launcher performance metrics:

- First stage reusability might reach early break-evens with a small amount of reuses (2-3) in terms of material resource depletion and mass disposed in ocean. Nonetheless it should be noted that the stages were not distinguished in terms of material decomposition, while reusability might require additional critical resources.
- It might not pay off for all reusability options in terms of GWP, especially for hydrocarbon fuelled stages, as a consequence of the impacts of increased propellant production, handling, storage and the launch event itself. If carbon neutral propellant production is attained it might be possible to mitigate the GWP from production if hydrogen, ammonia or methane are used as fuels.
- High sensitivity of the final impact to the O/F ratio was identified as a consequence of the high relative difference in oxidizer and fuel production, handling and storage emissions, secondary and incomplete combustion product emissions, and and its influence on the structural design and propulsion efficiency of the vehicle.
- Downrange landing strategies can be more sustainable in terms of all impact categories, especially for VTHL vehicles using the IAC method, especially in reduced OD.

- High sensitivity with cost optimal staging conditions was identified, especially for hydrogen stages, resulting from higher non mass optimal conditions. In addition, high staging velocities may result in real gas aerothermal effects during the first stage entry which may significant NO_x. This might depend on the stage ballistic coefficient (affected by propellant choice), its lift-to-drag capabilities and flight profile. Introducing an additional upper stage could mitigate the impact by reducing vehicle weight and allowing higher staging conditions, although only if the demisable material is kept within limits, or if made reusable, and at the expense of possible higher vehicle complexity and weight in the later. This indicates the need to account for environmental impacts early in the design phase as it might have conflicting considerations with respect to cost effectiveness.

- Propellant choices, hydrogen fuelled launchers achieved the best environmental performance in all environmental categories assessed, followed closely by ammonia launchers. RP-1 and propane based launchers showed significantly higher climate forcing and ozone depletion impacts, even when accounting for carbon neutral propellant production, as a consequence of their high soot content in the exhaust. Methane stages performed adequately because of the assumed reduced soot emissions. Nevertheless, given the uncertainty surrounding soot emissions and impacts from leakages in the production and handling phase, it might not be considered a more sustainable options when compared to hydrogen and ammonia based launchers, especially when considering its possible increased launch effort.[18]

- Environmental impacts from rockets might be significant at high launch rates constraining their use for certain applications and the economics of reusable vehicles. Mitigation of these with adequate design choices or even unconventional launch methods is therefore crucial.

- Internalization of costs from climate change through recent regulatory developments may surpass assumed launch costs of RLVs, highlighting the importance of early design for mitigation.

It should be noted that life cycle impacts are based on current industrial processes and may improve in the future. There are also additional impact categories which may vary considerably depending on design options, as the effect of the discarded launch vehicle components surviving demise, photo-chemical oxidation, particulate matter, cloud formation impacts and land and water use. The study also identifies that high uncertainty remains in the design strategies, life cycle impacts (as from propellant leakages or carbon neutral hydrocarbons), emissivity indexes, and especially in impacts from atmospheric pollutants during ascent and reentry. The weighting factors assumed based on emission species in terms of GWP and OD were based on aviation and ground based emissions, and are not representative of the impacts of launch events. These might affect the absolute and relative comparisons significantly, especially regarding potential impacts from black carbon, rocket exhaust and shock-wave induced NO_x production, demised material, and cloud formation. Alternative metrics as averaged temperature response and algorithmic environmental change functions could be more representative. Therefore, results from this study must be taken with caution and highlight the need for detailed studies on the microphyics of aerosols and impacts from the different emission profiles with state of art atmospheric modelling. These, and adequate approaches to weight at posteriori the various life cycle impacts, are necessary to enable design for mitigation while avoiding burden shifts.

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