Paul Erik Schabedoth

Life cycle assessment of rocket launches and the effects of the propellant choice on their environmental performance

Master's thesis in Industrial Ecology
Supervisor: Johan Berg Pettersen
July 2020

Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

NTNU
Norwegian University of
Science and Technology

Paul Erik Schabedoth

Life cycle assessment of rocket launches and the effects of the propellant choice on their environmental performance

Master's thesis in Industrial Ecology
Supervisor: Johan Berg Pettersen
July 2020

Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

NTNU
Norwegian University of
Science and Technology

Preface

This work represents the Master's thesis of Paul Schabedoth, as part of his Master's studies in Industrial Ecology at the Norwegian University of Science and Technology. This thesis was written in the form of a scientific article, in accordance with his supervisor Johan Berg Pettersen. The thesis is therefore following the layout and word count prescribed by the journal Acta Astronautica, where it will be submitted to as a manuscript.

Following the Master's agreement, signed by the author, his supervisor and the department of energy and process engineering, the tasks to be considered in this thesis were:

- Summarize the results of the literature research and the LCA of the production of the propellants performed in the preceding project thesis
- Identify the emissions released during the launch of orbital rockets
- Assess the induced environmental impacts of these emissions
- Perform a comparative LCA of the propellants including their production and the launch
- Conduct a benchmark, drawing from the results of the LCA and other relevant qualitative and quantitative aspects
- Perform a sensitivity analysis of the benchmarking
- Conduct a scenario analysis investigating the future development of spacefaring-related environmental impacts

Trondheim, the 4th of July

Paul Schabedoth

Table of Contents

Life cycle assessment of rocket launches and the effects of the propellant choice on their environmental performance

Paul Schabedoth[a]

[a]*Norwegian University of Science and Technology, Gressbanevegen 2, 7031 Trondheim, Norway*

ARTICLE INFO

Article history:
Received 4 July 2020

Keywords:
Environmental impact
Space launch
Propellants
Life Cycle Assessment
Space sustainability

ABSTRACT

The first life cycle assessment of the entire life cycle of currently used rocket propellants was performed. The focus of this assessment was on the global warming and stratospheric ozone depletion impact categories. The propellant consisting of unsymmetrical dimethylhydrazine and the oxidizer dinitrogen tetroxide was shown to be associated with 77.8±9.2 kg CO_2-eq., followed by hydrogen combusted with liquid oxygen and RP-1 combusted with liquid oxygen with an impact of 23.7±2.9 kg CO_2-eq and 17.3±9.2 kg CO_2-eq., respectively. Liquid methane and liquid oxygen had the lowest global warming impact with 7.5±1.2 kg CO_2-eq, while the ammonium perchlorate composite propellant was found to have a cooling impact of -18,7±29,3 kg CO_2-eq. The impacts of hydrogen, methane and hydrazine are driven by the energy demand of their production due to greenhouse gas emissions from fossil fuel combustion. The impacts of RP-1 and the solid propellant are dominated by emissions during the rocket launch. Black carbon emissions drive the global warming impact of RP-1, and the release of alumina particles causes the cooling impact of APCP. The combustion of the composite propellant releases 0.27±0.18 kg CFC-11-eq. through the release of chlorine and hydrogen chloride during the launch. The ozone depletion caused by the other propellants is negligible in comparison. The assessment of the global warming impact caused by the global propellant use in rocket launches in 2019 showed that it is negligible compared to global CO_2 emissions, whereas the launches cause 0,39% of the global emission of ozone depleting substances. The warming impact is currently dominated by the production processes of hydrazine. As hydrazine is phased out, the black carbon emissions from RP-1 become the driver of the global impact and the optimisation potential of the environmental performance through improvements of the production decreases. The use of methane and hydrogen should be emphasized to avoid the growth of both impacts.

1. Introduction

The prevailing opinion in the rocket and atmospheric community is that rocket launches do not have a significant impact on the global environment at current launch rates (Murray, Bekki, Toumi, & Soares, 2013). Research has proven this presumption and shown that their effect on global warming (GW) and the ozone layer is indeed small (Ross & Sheaffer, 2014; Ross, Toohey, Peinemann, & Ross, 2009). However, the number of annually launched rockets is expected to increase in the coming years as more private and governmental actors launch rockets into space, which will cause the GW and ozone depleting impact to increase significantly (Dallas, Raval, Gaitan, Saydam, & Dempster, 2020). Hence, measures to mitigate the environmental impacts might become necessary. The easiest measure to reduce the impacts of a rocket launch is to switch to a propellant with a low environmental impact. The environmental impacts of propellants over their entire life cycle, however, have never been studied. Preceding research allows for the identification of the propellant with the lowest environmental impacts from its combustion during the launch, but the studies are disregarding the impacts arising from the propellants' production and loading (Ross & Sheaffer, 2014; Ross et al., 2009). Meanwhile, Pettersen, Silva, Bergsdal, and Solli (2016) have performed a comparative assessment of the environmental impacts caused by the propellants' production and loading, but did not include the impacts arising from the launch.

The aim of this study is to fill this knowledge gap and investigate the environmental impacts of all currently used rocket propellants with a life cycle perspective. All processes regarding the production, loading and combustion of the propellants during the launch are analysed in this comparative life cycle assessment (LCA). To the author's knowledge, this marks the first time, that the entire life cycle impacts of rocket propellants have been assessed. The findings of this LCA are used to clearly identify the propellants with the lowest environmental impacts and to give an understanding of the importance of employing a life cycle perspective in this assessment. This helps to prevent the shifting of environmental impacts from one life cycle stage to the other (Hauschild, Rosenbaum, & Olsen, 2018). The quality of the results of the LCA is evaluated with an uncertainty analysis and the impact of the uncertainties is investigated by conducting a sensitivity analysis. The LCA is amended by performing an assessment of the impacts caused by global rocket launch activities in 2019 and, as far the author is aware, the first forecast projecting the development of the GW and ozone depletion impacts caused by rocket launches until 2050. The impact forecasts are used to provide an understanding of the drivers of the global impacts, and to highlight potential measures to mitigate the global environmental impacts, as well as to assess their necessity.

2. Background

2.1. Life cycle assessment of rocket propellants

Rocket propellants are combusted to provide thrust for a rocket's ascent and acceleration on its flight to space. A propellant always consists of fuel and oxidizer and is characterised by the large amount of energy released during its combustion. Only three liquid propellants and one solid propellant are currently used in orbital rockets as not many chemicals meet the needs of the space industry (Dallas et al., 2020). The solid propellant is an ammonium perchlorate composite propellant (APCP) and it is relying on aluminium as the fuel and ammonium perchlorate (AP) as the oxidizer, bound into a gel-like mass by the binder hydroxyl-terminated polybutadiene (HTPB) (Varghese & Krishnamurthy, 2017). Two of the liquid propellants consist of the oxidizer liquid oxygen (LOx), which is combusted with either highly refined kerosene, called rocket propellant-1 (RP-1), or liquid hydrogen (LH_2). The third liquid propellant consists of the fuel unsymmetrical dimethylhydrazine (UDMH) with the oxidizer dinitrogen tetroxide (NTO). The liquid propellants are hereafter only referred to by their fuel.

Rocket propellants, like any other product, interfere with the environment throughout their entire life cycle, which consists of the extraction of raw materials, the production of the propellants, their transport to the spaceport, and the use-phase, which includes fuelling and the launch (Klöpffer & Grahl, 2014). Studies investing these impacts are sparse (Dallas et al., 2020; Maury, Loubet, Serrano, Gallice, & Sonnemann, 2020). The environmental impacts caused by the production, transport and loading of rocket propellants has only been investigated by Pettersen et al. (2016) using LCA. However, the impacts caused by the combustion of all aforementioned propellants during the launch has never been analysed using LCA (Maury et al., 2020). A comprehensive study investigating the impacts of the entire life cycle of rocket propellants is still lacking. Only the European Space Agency (ESA) has performed LCAs covering the production of rocket propellants and the launch of the Ariane 5 and 6, as well as of some scientific missions (Chanoine, 2017; De Santis et al., 2013; Gallice, Maury, & del Olmo, 2018). However, ESA's efforts are naturally focussed on the rocket propellants used by European rockets, which are LH_2 and APCP (Arianespace, 2014, 2016; ESA, n.d.). The results of these studies are furthermore difficult to interpret as neither the data used in the LCAs, nor the assumptions applied were disclosed. Additionally, only the relative contributions of different processes in the life cycle of an Ariane 5 launch to the environmental impact scores are presented and these shares are conflicting. While Chanoine (2017) found the launch and thereby the combustion of rocket propellants to only cause a negligible percentage of the GW impact, De Santis et al. (2013) found the launch to cause nearly two thirds of the GW impact associated with the launch of one Ariane 5. These conflicting results only allow for the conclusion, that the magnitude of the launch impact is still uncertain and that it depends significantly on the assumptions of the study. Furthermore, they do not allow for a comparison of the propellants. Contrary to the studies mentioned above, it is therefore aimed in this study to provide full disclosure of all assumptions and data sources used in this LCA, in order to allow further research to be based on the results found here.

2.2. Environmental impacts of rocket launches

The most significant global impacts arising from the combustion of rocket propellants are GW and stratospheric ozone depletion (SOD) (Chanoine, 2017; De Santis et al., 2013). Other environmental impacts are also induced by the launch, but they are both sparsely researched and not deemed to be of high relevance for space applications (Dallas et al., 2020; De Santis et al., 2013). Therefore, only GW and SOD are investigated in the LCA performed in this study.

Nevertheless, it has to be acknowledged, that rocket launches do not only impact the climate and the ozone layer, but also cause soil and marine acidification, the depletion of fossil resources, eutrophication and the exposition of humans and ecosystems to toxic substances, amongst others (De Santis et al., 2013). Rocket launches cause acidification due to the deposition of metallic particles from the launch plume, however the impact is confined to a small area around the launch pad and to the use of APCP (Bennett & McDonald, 1998; Hinkle & Knott III, 1985; AE Jones, Bekki, & Pyle, 1995; National Aeronautics and Space Administration [NASA], 1995). The use of RP-1 and methane is depleting global fossil resources, and the release of nitric oxide (NO) during the combustion is causing eutrophication in water bodies, damaging ecosystems (Dallas et al., 2020). UDMH is severely toxic to both humans and ecosystems and the fallback of spent rocket stages to Earth has been polluting both marine and terrestrial ecosystems (Byers & Byers, 2017; Dallas et al., 2020). These impacts will not be shown by the LCA, as they have been omitted, but should be taken into account by stakeholders in the industry.

The biggest concern regarding the GW impact of launches is centred on black carbon (BC) and alumina emissions as Ross and Sheaffer (2014) pointed out in their study. The impact caused by CO_2 and H_2O emissions from the combustion was found to be negligible (Ross & Sheaffer, 2014). The authors also highlighted that BC emissions can accumulate in the stratosphere and mesosphere for up to four years where they reduce the reflectivity of the Earth and cause the absorption of more solar radiation. This heats up the atmosphere by inducing a radiative forcing. The current extent of the impact of launch related BC emissions has not been studied, however an increase in the number of launches from present levels, around 100 per year, to 1000 per year could lead to a similar radiative forcing as present-day aviation activities, and could induce a regional radiative forcing of up to 0.1 W/m^2 (European Space Policy Institute [ESPI], 2020; Ross, Mills, & Toohey, 2010). Ross and Sheaffer (2014) estimated that alumina particles have a similar warming impact on the climate as BC, since they discovered that it absorbs upwelling long-wave radiation and thereby contributes to global warming. However, they perceived this mechanism to be poorly understood. Their results were exclusively based on simplified emission data from Simmons (2000), which highlights the need to formulate a detailed emission inventory for this study.

While the impact of alumina particulates on the climate is highly uncertain, it is established knowledge, that APCP is the most harmful propellant for the ozone layer as its combustion emits hydrogen chloride (HCl), chlorine (Cl) and solid alumina particles (Bennett & McDonald, 1998). Cl emitted from APCP is driving catalytic ozone depleting reaction (World Meteorological Organization [WMO], 2018). HCl emissions are photolyzed by the UV-rich radiation in the upper atmosphere which releases active Cl and therefore also causes ozone depletion (WMO, 2018). Alumina particulates act as condensation platforms in the stratosphere and mesosphere, which facilitate ozone depleting reactions (Molina, Molina, Zhang, Meads, & Spencer, 1997). It was observed that the launch of one Space Shuttle used to deplete all ozone along its flight path, due to the emissions from its solid rocket boosters (Danilin, Ko, & Weisenstein, 2001; AE Jones et al., 1995). The global impact of APCP on the ozone layer is currently considered negligible (Danilin et al., 2001). It has been modelled that all rocket launches in 2009 only caused a global ozone loss of 0.03 percent, which might justify the exclusion of the launch industry from the Montreal

Protocol (Ross et al., 2009). However, there are considerable uncertainties in these models resulting from a lack of understanding of the combustion processes, a lack of detailed emission data, and the uncertainty of the development of the launch rate (Murray et al., 2013). Ross et al. (2009) have estimated that a weekly launch of the Space Shuttle would have caused two percent of ozone loss annually, showing that not only the GW impact, but also the SOD impact of rocket launches has a considerable sensitivity towards the launch rate. Despite liquid rocket engines not emitting Cl, HCl, or alumina, they do emit ozone depleting substances like hydrogen species (HOx) or water vapour (H_2O). Their impact is, however, dwarfed by the impact of HCl and Cl and were therefore not included in the assessment (Larson et al., 2017; Ross, Danilin, Weisenstein, & Ko, 2004).

3. Materials and methods

3.1. Life cycle assessment

LCA is used as the method of choice to investigate the environmental impacts of rocket propellants. It is especially suited to cover all stages of their life cycle and allows for the quantification of their impacts over a broad range of environmental impact categories, although this study is only focussing on GW and SOD (Hauschild et al., 2018). It is standardized in ISO 14040:2006 and ISO 14044:2006, which determine the structure of the study performed here and it consists of four phases (International Organization for Standardization [ISO], 2006a, 2006b). These are the goal and scope definition, the life cycle inventory analysis (LCI), the life cycle impact assessment (LCIA) and interpretation (ISO, 2006a). An LCA is assessing the environmental performance of a product system by compiling all emissions occurring in its life cycle in the LCI and multiplying these emissions with standardised characterisation factors (CF). The CFs aim to quantify the impact of each respective emission in the included environmental impact categories. The LCA calculations are performed using the software SimaPro 9.0 drawing from the database Ecoinvent v3 (PRÉ, 2020; Wernet et al., 2016).

3.1.1. Goal and scope definition

The goal of this LCA study is to analyse and compare the environmental impacts associated with the production and combustion of rocket propellants. The investigated propellants are RP-1, LH_2 and UDMH, together with their respective oxidizers, as well as APCP and the soon to be used fuel liquid methane (LCH_4) being combusted with LOx. LCH_4 was included in the assessment as the companies SpaceX and Blue Origin, as well as the ESA are working on methane fuelled rocket engines (Blue Origin, n.d.; ESA, 2017; SpaceX, n.d.). It is therefore likely, that LCH_4 will be an important rocket propellant in the future. This LCA is conducted to rank the propellants by their environmental performance and to deliver a general understanding of the environmental hotspots in their life cycle, as well as to act as a foundation for the impact forecast. The system boundary, denoting the included processes in the LCA, is from cradle to grave and therefore includes all stages of the lifecycle of the propellants, i.e. extraction of raw materials, production, transport, loading and launch, as well as the treatment of waste from the production, logistics and fuelling stages as illustrated in Figure 1. All life cycle stages except for the launch are from here on referred to as the production. The emissions from the launch are assumed to be released at ground level, as required by the definition of the characterisation factors (Ross et al., 2009; Sherwood, Dixit, & Salomez, 2018). The effect of afterburning is not investigated.

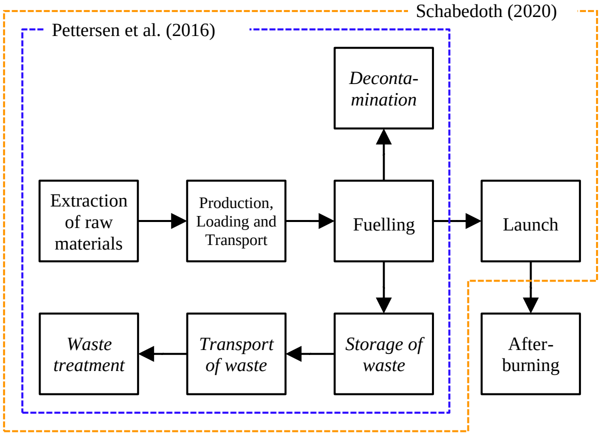

Figure 1 – The included processes in this LCA (dotted orange line) and in the LCA conducted by Pettersen et al. (2016) (dotted blue line). Processes in italics only apply to UDMH.

The goal and scope definition also includes the definition of the functional unit (FU), which is used to support a fair comparison between the propellants (Hauschild et al., 2018; ISO, 2006a). The function of rocket propellants is to be combusted to generate thrust. Fuel efficiency in terms of thrust generated per kg of propellant is therefore of the utmost importance. This is expressed with the specific impulse (I_{sp}) of a rocket engine (Turner, 2009). Although it is not a material parameter inherent to each propellant, Pettersen et al. (2016) estimated typical I_{sp} values of rocket engines fuelled by each of the five propellants. The FU applied here is the amount of each propellant, consisting of fuel and oxidizer according to the mixing ratios outlined in Table 1, needed to generate the same amount of thrust as the combustion of one kg of LOx and LH_2, hereafter referred to as the liquid hydrogen equivalent mass (H_2EM). This reference point is chosen since LOx & LH_2 yields the highest I_{sp} making it the most efficient fuel. The respective FU and I_{sp} values are outlined in Table 1. All environmental impacts calculated in the LCIA are expressed relative to the FU (ISO, 2006a).

The impact assessment method for the LCIA stage is determined in the goal and scope definition (ISO, 2006a). The assessment method governs the range of impact categories and specifies the respective CFs. In this study, the ReCiPe 2016 impact assessment method was employed (Huijbregts et al., 2016). ReCiPe 2016 contains specified CFs for three cultural perspectives, which are used to standardise assumptions regarding the time horizon of the impacts and their evidence base (Hauschild et al., 2018). The 'hierarchical' cultural perspective was employed in this study, as it is considered to be the default choice (Hauschild et al., 2018). For reasons outlined in Section 2.2. only the impact categories GW and SOD were included. ReCiPe was applied only to the LCIA of the production of the propellants, while the impacts of the launch were investigated using additional CFs.

3.1.2. Life cycle inventory analysis

The LCI phase describes the collection of data to model processes in the production system, to quantify their inputs, outputs, and emissions. The compilation of the emissions caused by the FU is called an inventory. The inventories compiled by Pettersen et al. (2016) covering the life-cycle stages of the propellants up to the launch were adopted for this work. Other systems of a rocket or the propulsion system were not included in the LCI. Pettersen et al. (2016) used only publicly available data for the compilation of the inventories and relied on the Ecoinvent v3 database for all generic background processes (Wernet et al., 2016).

Detailed data on the emissions of the propellants during the launch was not available in the scientific literature. Therefore, the emission indices, being the quantity of an emission per kg propellant combusted, of all five propellants was modelled using the tool Chemical Equilibrium with Applications (CEARUN) developed at NASA (McBride & Sanford, 1996). The mixing ratios, chamber pressures and frozen or equilibrium flow condition assumed by Pettersen et al. (2016) were used when running CEARUN to enable consistency across the studies. These parameters are outlined in Table 1. Pettersen et al. (2016) modelled all propellants, except for APCP, using the frozen flow condition, and applied the equilibrium flow condition for APCP.

Table 1 – Parameters adapted from Pettersen et al. (2016) used for the calculation of the LCI using CEARUN. All other parameters of the program were set at the default value.

Propellant	I_{sp} [s]	Mass per H_2EM [kg]	Mixing ratio	Chamber pressure [bar]
LOx &RP-1	339	1.319	2.29/1	60
LOx&LH_2	447	1.000	5/1	60
LOx&LCH_4	326	1.371	2.77/1	60
NTO&UDMH	320	1.397	2.1/1	10
APCP (AP/Al/HTPB)	280	1.596	68/18/14	60

It has to be noted that CEARUN does not model afterburning, the phenomena describing the continued combustion of under oxidized emission species when they mix with the surrounding air after exiting the rocket's nozzle (Ross & Sheaffer, 2014). Therefore, this LCI overestimates the amount of carbon monoxide (CO), oxygen (O), hydrogen (H) and nitrogen oxide (NO) emissions. CEARUN does also not predict the emission of BC. The modelled emission indices were coupled with the BC production rate specified by Ross and Sheaffer (2014), as their research showed the importance of BC for the GW impact of launches. They assumed 20 grams of BC to be produced by the combustion of 1 kg of RP-1. UDMH as well as APCP were assumed to emit 4 grams of BC per kg of combusted propellant, while LH_2 does not emit BC, considering the lack of carbon in the propellant (Ross & Sheaffer, 2014). LCH_4 was also assumed to not emit BC as has been demonstrated for the mixing ratio assumed here (Pempie, Vernin, & Entreprises, 2015; Preuss et al., 2008).

The emissions of elementary H and H_2, as well as of O and O_2 were summed up, as those species were assumed to have the same environmental impacts. Although Ross and Sheaffer (2014) focussed only on the emission of alumina particles, the combustion of APCP also produces other particulate aluminium species. These and the alumina emissions where also summed up. Combustion products present at below 0.1 grams per kg propellant were disregarded, assuming their impact to be negligible. The emissions were then scaled to 100% and verified using the modelling tool 'Rocket Propulsion Analysis' as well as through comparison with data found in literature, which can be found in Section A1 of the appendix (Ponomarenko, 2010; Ross & Sheaffer, 2014; Simmons, 2000).

3.1.3. Life cycle impact assessment

The environmental impacts associated with the FU are calculated in the LCIA by multiplying each emission compiled in the LCI with its respective CF in the two assessed impact categories. These CFs are usually prescribed by the impact assessment method. However, it is expected that the largest share of the emissions consists of near-term climate forcers (NTCF), an umbrella term for emissions with a short atmospheric lifetime (Intergovernmental Panel on Climate Change [IPCC], 2013). Contrary to well-mixed greenhouse gases, NTCFs only have a regionalised impact on the climate system and their impacts are associated with a larger uncertainty (IPCC, 2013). This poses problems for the LCIA performed here, as the IPCC has refrained from standardising the global warming potential (GWP) of NTCFs, which is the metric used in the GW impact category. The IPCC omitted the impacts of NTCFs as they are of little relevance for the long-term mitigation of climate change (IPCC, 2013). The GWP is a metric to express the impact of one kg of a compound on the climate, relative to the impact of one kg of CO_2 over a specified time horizon (IPCC, 2013). The time horizon of the GWP is set at 100 years, as prescribed by the "Hierarchical" cultural perspective (Huijbregts et al., 2016). The WMO has also not defined ozone depletion potentials (ODP) of emissions with a short lifetime as of now (WMO, 2018). The ODP is the relative metric used in the SOD category, quantifying the capability of one kg of an emission to destroy stratospheric ozone relative to the ozone-depleting effect of one kg of CFC-11 (WMO, 2018). GWPs therefore had to be adapted from preceding research, as depicted in Table 2, while the ODPs were estimated.

The GWP of the NTCFs varies significantly between different studies, as can be seen in Table 2. This is related to different experimental designs, different treatment of transport processes and varying assumptions regarding background levels of ozone and methane (IPCC, 2013). This highlights the uncertainty of the climate impact of NTCFs. Furthermore, most of the GWPs were calculated for emissions on ground level. Only the varying impacts of H_2O and NO depending on the altitude of their emission have been investigated by Fuglestvedt et al. (2010). The warming impact of H_2O increases with the altitude of its emission, while NO was found to warm, instead of cool when emitted higher up. The GWP of H_2O and NO emissions at high altitudes is deemed to be more accurate when analysing rocket launches. However, they were not applied in this study as altitude dependant GWPs of the other NTCFs are not available and since the use of the ODP metric requires emissions to be released at ground-level (Ross et al., 2009). It was preferred to assume all emissions to be released at ground level in order to ensure common assumptions for all emissions and both impact categories . Where available, GWPs for ground level emissions calculated by Fuglestvedt et al. (2010) were adopted. Only ground-level emissions of H_2O and H were omitted from their study. Their GWPs were therefore adopted from Sherwood et al. (2018) and Derwent (2018), respectively.

Table 2 – Overview over the varying GWPs of the emission species across studies. The GWPs are presented in kg CO_2-eq. Adopted GWPs in this LCA are printed in bold.

Emission	Mean	Min	Max	Source
CO	3.2			Derwent, Collins, Johnson, and Stevenson (2001)
	2			**Fuglestvedt et al. (2010)**
	2.7	1	4.4	Daniel and Solomon (1998)
	5.3	3	7.6	Shindell and Faluvegi (2009)
CO_2	**1**			**IPCC (2013)**
H_2O	**0.002**	-0.001	0.005	Sherwood et al. (2018)
	0.2			At 12 km altitude; Fuglestvedt et al. (2010)
	4.3			At 20km altitude; Fuglestvedt et al. (2010)
H_2	**4.3**	0	9.8	**Derwent (2018)**
	5.8			Derwent et al. (2001)
OH	**-6**			Estimate based on OH oxidising methane
N_2	**0**			**de Vries, Kros, Reinds, and Butterbach-Bahl (2011)**
NO	4.5			Surface emission in NH; Derwent et al. (2001)
	-277.1			Aircraft NOx; Derwent et al. (2001)
		-2.1	71	Aircraft NOx; Fuglestvedt et al. (2010)
	-159	-80	-238	Shindell and Faluvegi (2009)
	-11			**Fuglestvedt et al. (2010)**
BC	900	100	1700	Bond et al. (2013)
	460			**Fuglestvedt et al. (2010)**
	830	390	1270	Bond, Zarzycki, Flanner, and Koch (2011)
	1060			Lund et al. (2017)
OC	-77			Lund et al. (2017)
	-69			**Fuglestvedt et al. (2010)**
	-46			Bond et al. (2011)

The emission of alumina particulates poses an obstacle for the LCIA, as neither their GWP nor ODP has been defined, although research has shown that they have an impact on the climate by reflecting solar radiation, absorbing upwelling longwave radiation and that they support ozone depleting reactions when emitted in the stratosphere (Molina et al., 1997; Ross & Sheaffer, 2014). However, the impact of the alumina particulates on the climate is poorly understood (Ross & Sheaffer, 2014). While Ross and Sheaffer (2014) found them to have a warming impact when emitted in the stratosphere, the IPCC (2013) is generally associating tropospheric emissions of brightly coloured particles with a moderate cooling impact on the climate. Considering the lack of consensus and further studies on alumina particulates, it was chosen to assume that the particulates have a cooling impact in this study, as it could not be extrapolated from Ross and Sheaffer (2014) if the particulates also have a warming impact on the climate when emitted at ground level. The GWP of a similar particulate emission, organic carbon (OC), was adopted for the GWP of alumina particulates, as no GWP for alumina has been developed. Its impact on the ozone layer was omitted, as it is poorly understood and could therefore not be quantified (Ross et al., 2009).

The assessment of SOD was limited to the effects of NO, Cl and HCl. Despite the emission of H, OH and H_2O from the propellants also having an effect on the ozone layer, these were assumed to be small compared to the direct effect of the three named chemicals (Ross et al., 2009). No ODP for NO was found in the literature, but an ODP of 0.015 kg CFC-11-eq. for N_2O is stated by WMO (2018). N_2O is largely inert in the atmosphere, but dissociates into NO, which is catalytically destroying ozone (WMO, 2018). The ODP value of N_2O was therefore assigned to NO. The ODP of N_2O is highly dependent on background CO_2 and methane levels. The value adopted here marks the lower boundary of the ozone depleting impact of N_2O. The WMO has also not defined ODP values for Cl and HCl, potentially because elementary chlorine usually does not reach the stratosphere if emitted at ground level. The ODP of these two compounds therefore had to be estimated by analysing the relationship between the chlorine content of chlorofluorocarbons (CFC) and their ODP. The chlorine content was defined as the number of chlorine atoms in one molecule of a CFC divided by the number of atoms in that molecule. This relationship for CFCs can be seen in Figure 2, drawing from WMO (2018). A linear regression was performed to estimate the ODP of Cl and HCl for their chlorine content of 1 and 0.5, respectively. These were found to be 1.53 kg CFC-11-eq. for Cl and 0.90 kg CFC-11-eq. for HCl.

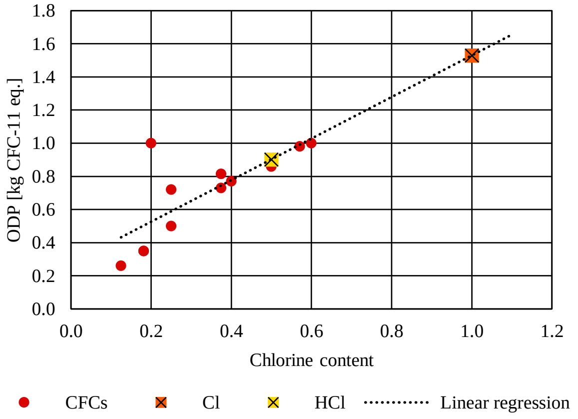

Figure 2 – Estimation of the ODP of Cl and HCl based on the analysis of the ODP and chlorine content of CFCs. The ODP of the CFCs were adopted from WMO (2018).

The adopted and estimated CFs were not applied to the LCIA of the production, as their effect on the results of the production stages was found to be minimal. Their inclusion in the production stages was furthermore found to increase the uncertainty in the LCIA of that stage considerably, which was deemed to be undesirable.

3.2. Uncertainty analysis

Uncertainty is not only prevalent in the CFs, but also in the composition of the exhausts of the five propellants, as well as in the LCIs compiled by Pettersen et al. (2016) Uncertainty in the adopted inventories stems largely from a lack of technology correlation, meaning that the processes modelled by Pettersen et al. (2016) might not be precisely representing the actual processes happening during the production of the propellants. The uncertainty in the emission inventory from CEARUN, as well as in the CFs is unknown and had to be estimated. All these uncertainties propagate to the results of the LCA. As a ranking of the environmental performance of the propellants is the goal of this comparative LCA, an uncertainty analysis was deemed necessary to assess the quality of this ranking. This was done through a Monte-Carlo analysis, which allows for a suitable assessment of the uncertainties within the inventory by calculating the impact scores assuming pseudo-random values for the inventory and CF data, which is repeated iteratively (IPCC, 2006). The pseudo-random values are generated from a probability density function. The Monte-Carlo analysis of the production and loading of the propellants was performed in the software SimaPro 9.0 applying the uncertainties in the inventories as defined by Pettersen et al. (2016), who used the pedigree matrix approach for their assessment (Weidema et al., 2013). SimaPro yielded the mean and the standard deviation of the GW and SOD impacts of each propellants' production. These values were then used for the Monte-Carlo analysis of all life cycle stages using the tool Simulación (Varela, n.d.). Simulación was employed because SimaPro 9.0 does not allow for uncertainty in CFs. A truncated normal distribution was used as the probability density function for all emission indices of the propellants. The mean of the truncated normal distribution was set at the output of CAERUN and a standard deviation of 35 percent of the mean was assumed. The lower and upper boundaries were set at zero and one kg emission per kg propellant combusted, respectively. Standardized CFs contain an uncertainty of 35 percent (Hauschild et al., 2018). A standard deviation of 70 percent of the mean was therefore deemed reasonable to presume for all non-standardised GWPs and ODPs in this study. A truncated normal distribution was presumed for the distribution of all ODPs and most GWPs, with the lower boundary being set at zero and the upper boundary being set at 1000 kg CO_2-eq. or 1000 kg CFC-11-eq. Only the GWP of H_2O was assumed to be normally distributed, considering that its GWP is close to zero, while the GWP of CO_2 does not contain uncertainty. 10,000 iterations were calculated for each of the two impact categories.

3.3. Sensitivity Analysis

To uncover how much changes in the inventory or the CFs affect the results of the LCA, a sensitivity analysis was conducted. The focus of this is upon the relative sensitivities, which describe the change in the impact score Sc of a propellant p caused by a change in the GWP or ODP of an emission compound, as well as to changes in the impact score of the production (Saltelli, Tarantola, Campolongo, & Ratto, 2004). The relative sensitivity $\bar{S}$ of propellant p in the impact category IC to a change in the CF of the emission e can be calculated according to Equation 1 and the relative sensitivity of the score towards changes in the impact score of the production $Sc_{IC,p,prod}$ is calculated following Equation 2. These equations yield a percentage score, indicating the relative increase or decrease of the impact score induced by a hundred percent increase in the parameter in question. The relative sensitivity of a propellant to a change in the characterisation factor is dependent on $EI_{p,e}$, being the quantity of emission e per kilogram of propellant p combusted.

$$\bar{S}(Sc_{IC,p}, CF_{IC,e}) = \frac{dSc_{IC,p}}{dCF_{IC,e}} \cdot \frac{CF_{IC,e}}{Sc_{IC,p}} = \frac{EI_{p,e} \cdot CF_{IC,e}}{Sc_{IC,p}} \tag{1}$$

$$\bar{S}(Sc_{IC,p}, SC_{IC,p,prod.}) = \frac{dSc_{IC,p}}{dSC_{IC,p,prod.}} \cdot \frac{SC_{IC,p,prod.}}{Sc_{IC,p}} = \frac{SC_{IC,p,prod.}}{Sc_{IC,p}} \tag{2}$$

3.4. Impact forecast

The launch industry is expected to grow rapidly over the coming decades (Dallas et al., 2020; Fortune Business Insights, 2020). The same trend is expected for the number of rocket launches. At the same time the global rocket fleet is changing. New launchers are being developed, either superseding existing launchers or being developed specifically for flights to the Moon and Mars, which will change both the amount and the type of propellant being used globally. A forecast of the GW and SOD impact caused by the propellant use of rockets was therefore performed in order to analyse how large the current global impacts of the rocket propellant use are and how their magnitude is expected to change in the future. Long-term projections about the development and growth of the space launch market do not exist, nor was information, on how the market share amongst the launchers will change, found. A quantitative forecast could therefore not be performed. An adapted form of the so-called IPAT equation was used to perform a semi-quantitative forecast of the global GW and SOD impact between 2019 and 2050 (Chertow, 2000). The IPAT equation allows for the estimation of environmental impacts based on the three independent variables population, its consumption of goods, called affluence and the technology used for their production (Chertow, 2000). This is adapted to Equations 3 and 4 to analyse the impacts of global rocket launches in the categories GW and SOD, where $n(t)$ is the number of annual rocket launches, representing the population, $PC(p, t)$ is the consumption of each of the five propellants p of an average rocket in the year t, as an adapted affluence. GW or SOD denote the impact on the climate or the stratospheric ozone layer per kg of each propellant, which is representing the technology.

$$GW_{global}(t) = n(t) \cdot \sum_{p} PC(p,t) \cdot GW(p) \tag{3}$$

$$SOD_{global}(t) = n(t) \cdot \sum_{p} PC(p,t) \cdot SOD(p) \tag{4}$$

These variables were defined only based on assumptions and, thus, contain significant uncertainties. The results should therefore be interpreted with caution. The size of the global launch service market is expected to grow by 14% annually between 2019 and 2026 (Fortune Business Insights, 2020). Assuming continued exponential growth, the number of launches in 2050 is reaching 590, up from 103 in 2019 (European Space Policy Institute [ESPI], 2020). The consumption of an average rocket of each of the five propellants in 2019 was calculated from the total amount of propellant used in all orbital launch activities in the base year 2019. Its change in time was estimated based on industry trends as outlined in Section A2 of the appendix, where all underlying assumptions are described in more detail. The GW and SOD impact per kg propellant was adopted from the LCA.

4. Results

4.1. Life cycle inventory analysis

The results of the inventories for all production stages are described in detail in Pettersen et al. (2016) and will not be presented in this section. They were compiled for the production of the chemicals in plants across the world, from where they are transported to the European space port in French Guiana. There they are loaded into the rocket. In Table 3 is the LCI of the launch depicted. This represents the emissions resulting from the combustion of the propellants. The results are shown per kg propellant combusted and not per H_2EM for easier comparability. The table shows that the predominant emissions from the combustion of RP-1 and LCH_4 are CO, CO_2, and H_2O. These emissions make up 92.8% and 95.3% of the exhaust of the respective propellants. The two propellants also emit small amounts of H, O, and hydroxyl (OH). RP-1 additionally emits 20 g of BC. The exhaust from the combustion of LH_2 consists mainly of water vapour, making up 90.7% of the exhaust. 6.4% of the exhaust is H while the remainder is O and OH. The largest chemical species in the exhaust of UDMH is nitrogen, which accounts for 35.3%. Together with CO, CO_2 and H_2O, N emissions make up 95.2% of the exhaust, the remainder being H, O, OH, NO and BC. The largest share of the exhaust of APCP is made up by the solid alumina particulates together accounting for 34.2% of the exhaust. CO is the second largest species present in the exhaust of APCP, followed by HCl and H_2O.

Incomplete combustion occurs for all five propellants, as shown by the presence of CO, H and OH. These incomplete combustion products are reactive compared to their stable counterparts CO_2 and H_2O and therefore interfere with the atmospheric chemistry (Daniels, 1989).

4.2. Life cycle impact assessment

Figure 3a (GWP) and Figure 4a (SOD, in logarithmic scale) show the results of the LCIA of the five propellants in the two impact categories per H_2EM. The errors bars in the figures highlight the 68% confidence interval. UDMH causes the highest GW impact with 77.8±9.2 kg CO_2-eq. per H_2EM, followed by LH_2 and RP-1 with an impact of 23.7±2.9 kg CO_2-eq and 17.3±9.2 kg CO_2-eq., respectively. UDMH having the largest GW impact is uncontested, despite the uncertainty range. LCH_4 has an impact of 7.5±1.2 kg CO_2-eq. and one H_2EM of APCP produces a cooling impact of -18.7±29.3 kg CO_2-eq. APCP might therefore also yield a warming impact. Generally, it can be observed, that propellants, where the GW impact is dominated by the production processes, contain a lower uncertainty compared to the launch-dominated propellants. This points towards the LCIA of the launch containing more uncertainty than the inventories compiled by Pettersen et al. (2016). It also highlights the large uncertainty of the impact of BC and alumina particulates.

The impact of the production of fuel and oxidizer is dominating the GW scores of LH_2, LCH_4 and UDMH with the production causing 99%, 61% and 68% of the impact, respectively. In the case of LH_2, the combustion only produces H_2O, H and OH), all of which are not strong climate forcers (Figure 3b), while the production of the fuel LH_2 itself is very energy-intensive. It was assumed to be produced through a two-stage reforming process (Pettersen et al., 2016). First, methanol is produced from natural gas and then shipped to the spaceport. Onsite, H is generated from methanol. The warming impact of this production is caused by a share of the energy used in the production stemming from fossil fuels. The impact of the production of LOx amounts for 2.5 kg CO_2-eq., which is related to the energy requirements of liquid air separation, and the use of fossil energy therein. One H_2EM of LCH_4 causes a GW impact of 7.5 kg CO_2-eq., The launch is responsible for the emission of 1.1 kg CO_2-eq. mainly caused by the warming impact of CO. The production of LCH_4 and LOx cause a similar warming impact with 3.4 and 3 kg CO_2-eq. per H_2EM, respectively. The production of LCH_4 from natural gas does not require large amounts of electricity compared to other fuels, so that roughly half of its warming impact is related to the construction of the steel storage tanks required to hold the fuel. The large GW impact of the production of UDMH is founded in the energy demand of the production of the fuel UDMH and the energy use of the waste treatment of NTO. UDMH was assumed to be produced through a complex production chain by distilling a synthesis liquor consisting of various chemicals. This distillation, as well as the production of each chemical requires heat and electricity, which was found to be partly supplied by fossil fuels, thus driving the GW impact. The contribution of NTO is caused by the waste treatment process, where direct GHG emissions happen during the incineration of waste generated in the fuelling. A further impact stems from the energy demand of nitrogen separation from air. Nitrogen is needed to purge all fuelling equipment from NTO remains in the fuelling system. The GW impact caused by the combustion of UDMH is next to negligible, as it only causes 3.2 kg CO_2-eq. The warming impact of the launch is dominated by the emission of BC, causing 77 percent of the launch impact of UDMH, followed by CO emissions, as presented in Figure 3b. The CO_2 emissions are negated by the emission of OH. The impacts of H and NO emissions are negligible.

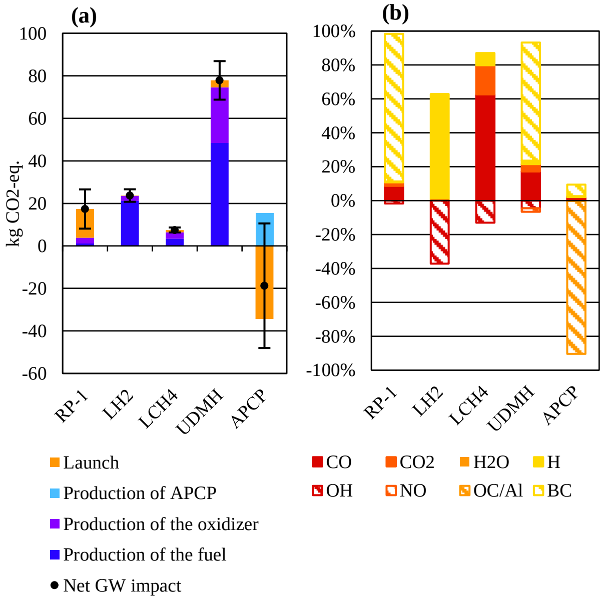

Figure 3 – Results of the LCA in the category global warming per H_2EM (a) with the error bars representing the 68% confidence interval and the shares of each emission at the launch impact (b).

Table 3 – Overview over the exhaust composition of the five propellants. Results are given in kg per kg propellant combusted.

Propellant	CO	CO_2	H_2O	H	O	OH	N_2	NO	Al	HCl	Cl	BC
LOx&RP-1	0.456	0.222	0.250	0.012	0.011	0.029	0	0	0	0	0	0.020
LOx&LH_2	0	0	0.907	0.064	0.002	0.027	0	0	0	0	0	0.000
LOx&LCH_4	0.344	0.187	0.422	0.018	0.005	0.024	0	0	0	0	0	0
NTO&UDMH	0.227	0.114	0.258	0.013	0.006	0.020	0.353	0.005	0	0	0	0.004
APCP	0.280	0.017	0.067	0.026	0.001	0.009	0.081	0.001	0.342	0.148	0.025	0.004

13.5 kg CO_2-eq. of the 17.3 kg CO_2-eq. caused by one H_2EM of RP-1 can be attributed to the combustion of the propellant. 92% of this impact is related to BC emissions, with CO causes most of the remaining impact (Figure 3b). The production of RP-1 is causing a low warming impact of 1.2 kg CO_2-eq. while the production of LOx is causing 2.7 kg CO_2-eq. The impact of the fuel production is related to the energy use during the reforming of kerosene, but it is also impacted by the energy needed to manufacture its storage tanks, in which RP-1 is shipped to French Guiana. The net cooling impact of APCP makes it the most beneficial propellant in terms of GW. The emission of 15.6 kg CO_2-eq. per H_2EM from the production, and the impact of the emissions released during the launch are offset by the cooling effect of the released alumina particulates. The warming impact of the production is related to the energy requirements in the production of both aluminium and ammonium perchlorate, which are satisfied with non-renewable sources. The production of HTPB is not responsible for significant CO_2 emissions.

APCP is the most impactful propellant on the stratospheric ozone layer, as Figure 4a (in logarithmic scale) shows. It causes 0.27±0.18 kg CFC-11-eq. per H_2EM and is thereby associated with an impact three orders of magnitude larger than UDMH, which has the second largest impact with 0.16±0.15 g CFC-11-eq. per H_2EM. The launch is dominating their performances in this impact category with the launch emissions causing essentially 100% of the impact of APCP and 71% of UDMH's impact. The emissions of the other three propellants were assumed to not have an impact on the ozone layer. Their impacts are thereby only caused by their production processes. LH_2 was found to emit 17.7±5.6 mg CFC-11-eq. per H_2EM, and the production of RP-1 and LCH_4 causes the emission of 4.24±1.2 and 4.75±1.4 mg CFC-11-eq. per H_2EM. The impact of the production processes is related to the minor release of ozone-depleting substances during the generation of energy from fossil fuels in the production of all propellants.

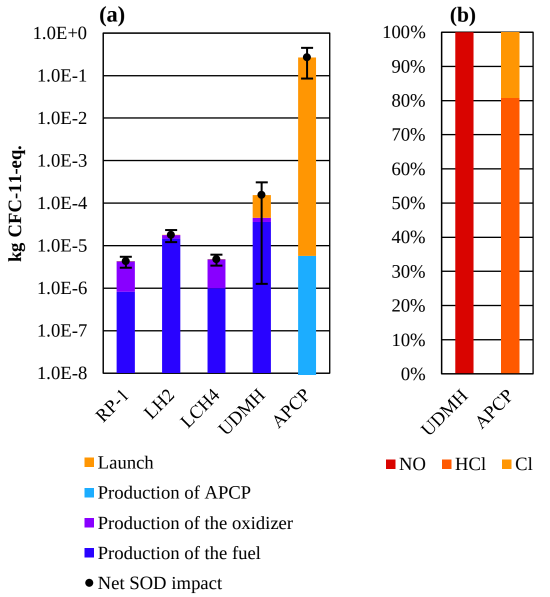

Figure 4 – Results of the LCA in the impact category SOD (a, in logarithmic scale) with the error bars representing the 68% confidence interval and shares of the emissions at the launch impact (b).

The beneficial cooling effect of APCP is therefore counterweighed by the large stratospheric ozone depletion impact the direct emissions of Cl and HCl cause during the launch. APCP is the only propellant that releases chlorine during its combustion and therefore causes the largest SOD impact of the five investigated propellants. UDMH and APCP are both emitting NO, also an ozone depleting chemical. Its contribution to the SOD impact of APCP is negligible, as the assumed ODP of NO is significantly lower than the ODPs of Cl and HCl. However, NO dominates the SOD impact of UDMH. This is presented in Figure 4b.

The LCA hints towards LCH_4 being the most environmentally friendly propellant. Both, its production, and its combustion produce little greenhouse gases and its exhaust products are not expected to have a significant impact on the ozone layer. This conclusion can be made despite the uncertainties in the LCA study, as shown with the error bars representing the 68% confidence interval in Figure 3a and 4a.

4.3. Sensitivity analysis

The results of the sensitivity analysis for the impact category GW, depicted in Figure 5a, show that the results of the LCA of LH_2 and UDMH in the impact category GW are virtually unaffected by changes or underestimations of the GWPs of the emission species. Their score is only affected the be the impact score of the production. The GW of LCH_4 is slightly affected by the GWP of CO. A doubling of this GWP increases the score of LCH_4 by 13%, whereas a doubling of the production impact increases the score by 85%. As expected, the GW impact of RP-1 is highly influenced by the GWP of BC. An increase of this GWP by 100% leads to a 70% higher result in that impact category, whereas a similar change in the GWP of CO or the global warming score of the production of the propellant only increases the result by 7% and 22% respectively. The impact score of APCP in GW is highly influenced by the GWP of the alumina particles. APCP's cooling impact is 205% larger, if a GWP of -138 instead of -69 kg CO_2-eq. is selected. An increase in the GWP of BC or the global warming impact of the production by hundred percent would reduce the cooling effect by 84 and 16 percent, respectively. Similarly, does a positive GWP of alumina particulates also induce a significant change of APCPs GW impact.

The SOD impacts of RP-1, LH_2 and LCH_4 are only determined by the SOD impact of the production of the three propellants, as shown by Figure 5b. The final score of UDMH in SOD is largely influenced by the ODP of NO. A hundred percent increase in NO's ODP yields a 71% higher SOD score. A correspondent increase in the impact of the production leads to the final score being 29% higher. The impact of the production is negligible for the SOD score of APCP. However, it is highly influenced by the ODPs of HCl and Cl. A doubling of either of these two yields an 81% and 19% higher final score, making the emission of HCl more significant for this impact category.

The parameters having the largest impacts on the results of the propellants in the GW category is the impact score of the production of LH_2, LCH_4 and UDMH, and the GWP of BC and the alumina particulates for RP-1 and APCP, respectively. The results of RP-1, LH_2 and LCH_4 in SOD are determined by the production impact, as well as by the ODP of NO, in the case of UDMH, and the ODP of HCl for APCP.

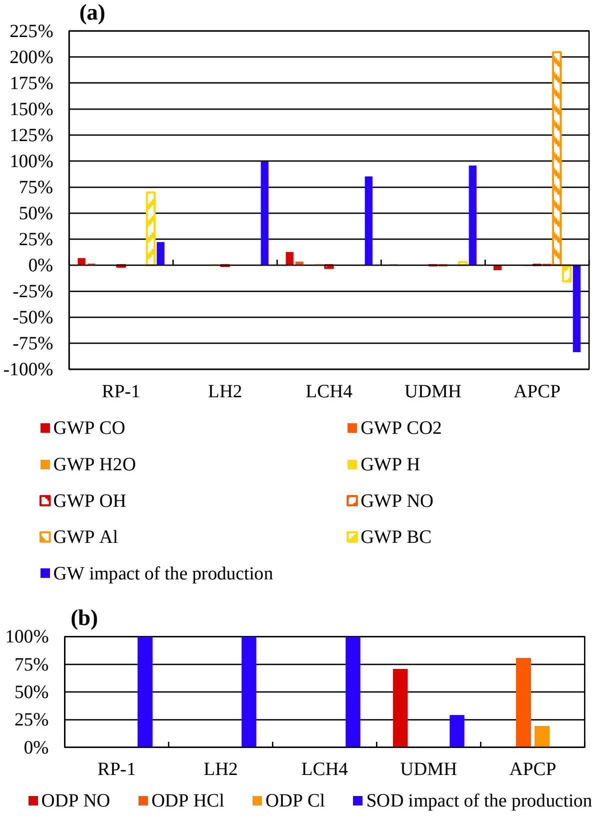

Figure 5 – Results of the sensitivity analysis for the impact categories GW (a) and SOD (b).

4.4. Impact forecast

Figure 6a to 6e present the results of the impact forecast using the adapted IPAT equation. Figure 6a shows, that the global rocket propellant consumption is going to increase from 33.5 kt in 2019 to 274.8 kt in 2050. This is driven by the fivefold growth in the number of rocket launches, up from 103 in 2019 to an estimated 590 in 2050, and the increase of the average propellant consumption per launch (ESPI, 2020). UDMH is phased out as a propellant by 2031 but is making up 33% of the total propellant consumption in 2019. RP-1 becomes the dominating propellant in 2050, climbing from a share of 42% in 2019 to 59% in 2050. The shares of LH_2 and APCP at the total propellant use remain consistent over the modelling timeframe. The use of LCH_4 increases significantly after the introduction of the Starship in 2021 to a share of 18% in 2050. Figure 6b shows the development of the related global warming impact in the same timeframe, which is increasing from 0.79 Mt CO_2-eq. in 2019 to 2.5 Mt CO_2-eq. in 2050. The impact is therefore rising less significantly than the propellant use, which is related to the phasing out of UDMH. Although only one third of the propellant burned in 2019 is UDMH, it is responsible for 77% of the global warming impact in that year. Its replacement with less impactful propellants can clearly be seen in the reduction of the global impact in the second half of the 2020s. Starting in this period, the impact caused by the production and combustion of RP-1 is starting to dominate the propellant related GW impact. Although RP-1 only causes 24% of the impact in 2019, it is dominating the global impact by causing 85% in 2050. RP-1 being the dominantly used rocket propellant was therefore identified as one of the main drivers of the growth of the GW impact. This is also shown by Figure 6d, where the warming impact caused by the production and the warming impact caused by the launch are contrasted. The production of the rocket propellants causes 94% of the net impact in 2019, but its share decreases to only 65% in 2050, as UDMH gets phased out and RP-1's share is increasing. This share only refers to the net impact, which does not deliver an accurate picture. Alumina particulates were assumed to have a negative GWP, which causes its release during the launch to cause a net cooling effect. This cooling effect is dampening the impact of the launches, as can be seen in Figure 6d. Ignoring the alumina emissions, the share of the impact of the production at the gross GW impact drops to only 48% in 2050 (Figure 6d). The launch impact furthermore increases from 0,18 Mt CO_2-eq. in 2019 to 1,8 Mt CO_2-eq. in 2050. This is mainly related to the increased BC emissions from RP-1. The alumina emissions therefore act as a sink, dampening the warming impact of the BC emissions by RP-1.

Figure 6c and 6e show the results of the impact forecast for the development of the global SOD impact. The combustion of APCP during the launch is dominating this impact over the whole timeframe. Neither the production of the propellants, nor the combustion of the liquid propellants is contributing significantly. The global impact is rising from 1.62 kt CFC-11-eq. in 2019 to 6.38 kt CFC-11-eq. in 2050 scaling with the increase of the launch rate and the average use of APCP.

5. Discussion

5.1. Discussion of the results

This LCA was conducted to uncover the GW and SOD impacts of the production and combustion of rocket propellants. The propellant mix of UDMH and NTO was found to be associated with the largest GW impact, causing the emission of 77.8 kg CO_2-eq. per H_2EM. LH_2 causes a GW impact of 23.7 kg CO_2-eq. per H_2EM, RP-1 causes 17.3 kg CO_2-eq. and LCH_4 only leads to the emission of 7.5 kg CO_2-eq. APCP was found to have a net cooling impact of -18.7 kg CO_2-eq. However, APCP is causing significant SOD with the emission of 0.3 kg CFC-11-eq. per H_2EM while the other propellants are not associated with a significant ozone depleting impact.

The combustion of LH_2, LCH_4 and UDMH does not contribute considerably to their respective GW impacts, as no strong greenhouse gases are emitted. The combustion of RP-1 causes the emission of black carbon, which is dominating RP-1's warming impact, while the combustion of APCP is releasing alumina particulates, which were assumed to have a cooling effect on the climate in this study. The alumina particulates drive the cooling impact of APCP. The results were used to perform a forecast of the GW and SOD impacts caused by the annual, global rocket launches between 2019 and 2050. The phasing out of UDMH was found to have a large effect on the global impact, while RP-1 becomes the dominant cause of the warming impact towards the end of the modelled time horizon. Furthermore, the share of the impact caused by the global propellant production is falling, which decreases the efficiency of climate change mitigation efforts, since these can only be achieved within the production processes. The global SOD impact is essentially only caused by the combustion of APCP and is projected to rise with the annual launch rate.

Preceding studies on the sustainability aspects of rocket launches are sparse and a systematic assessment of the environmental impacts of rocket propellants including the launch has never been performed. Therefore, the findings presented here cannot be compared with much preceding research. The findings of the LCA are in line with the work of Ross and Sheaffer (2014). The authors of this study concluded that CO_2 and H_2O emissions during the launch have a negligible impact on the climate whereas the largest impacts are caused by the emission of BC and alumina particulates. Therefore, the authors recommended the use of LH_2 in orbital rockets, based on its launch emissions. This is a finding also mirrored by this LCA, as the combustion of LH_2 only causes a negligible impact. However, the high energy demand of the production of LH_2 causes it to have the second largest GW impact of the five propellants. Only if the impacts from the production processes are reduced, is LH_2 a recommendable propellant. This highlights the value of a life cycle perspective when investigating the environmental perfor-

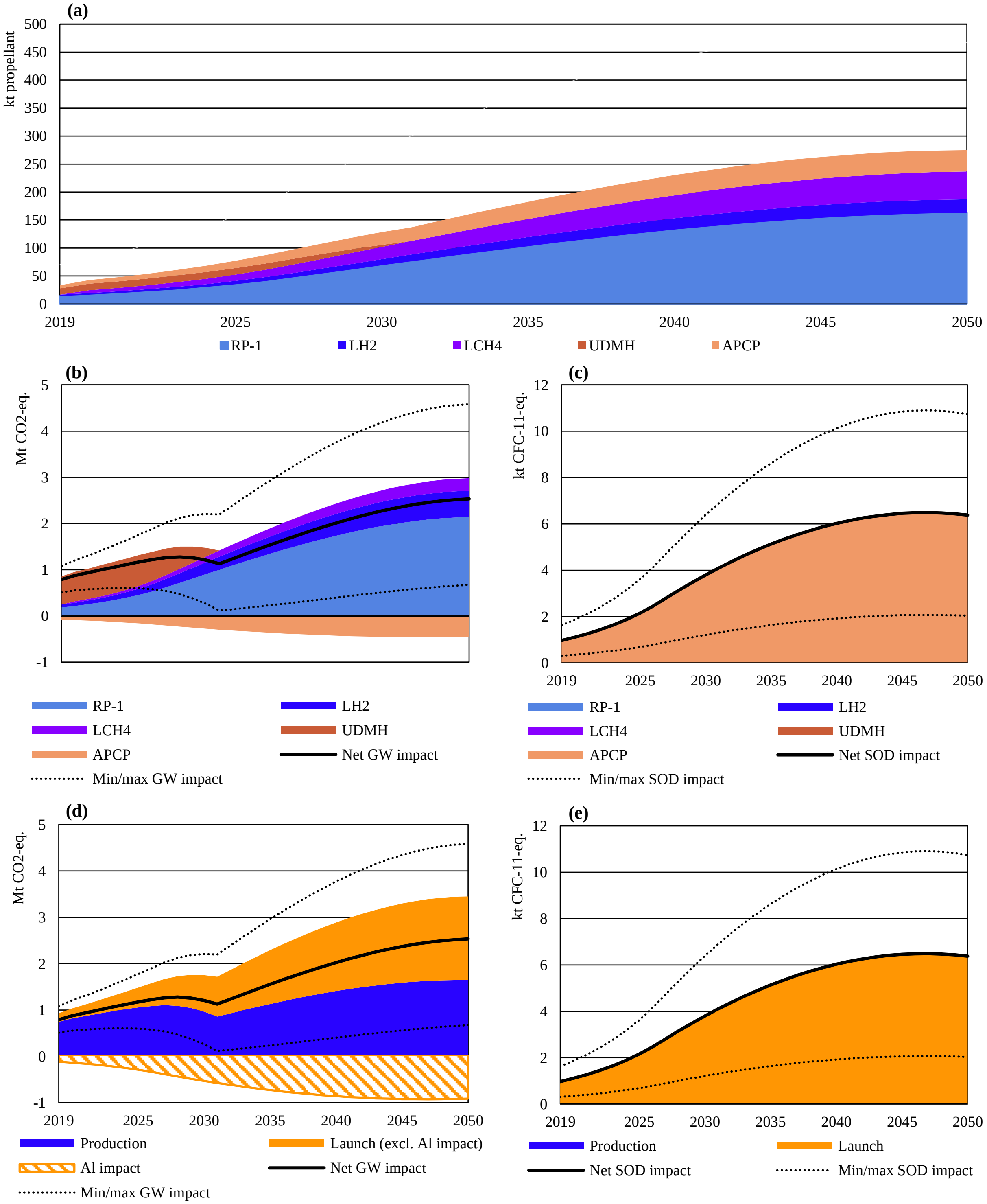

Figure 6 – Results of the impact forecast showing the global, annual propellant consumption (a), the annual GW and SOD impact caused per propellant (b, c) as well as the shares of the GW impact (d) and SOD impact (e) caused by the production and the launch.

mance of products, as only a life cycle perspective allows for the discovery of such aspects. As LCH_4 was not included in their study, can the results of the LCA of methane not be verified. Nevertheless, does this LCA see LCH_4 as the propellant with the least GW impact.

The time horizon of the GWP metric has a major impact on the results in the GW category. The shorter the chosen time horizon of the impact metric is, the larger the influence of NTCFs becomes (IPCC, 2013). This LCA is therefore highly variable towards the chosen time horizon, as the GW impact arising from the combustion of the propellants is largely related to the emission of NTCFs. The GW impacts of propellants increase if a shorter time horizon is used, which would alter the findings of this study. Furthermore, the GWP metric overestimates the impact of NTCFs on the climate, as it is an integrated metric (IPCC, 2013). This might help to interpret their domination of the GW impact category. Applying a different metric like the global temperature change potential (GTP) might alleviate this issue, as this is more accurately capturing the impact of NTCFs (IPCC, 2013). However, the GTP concept is not complying with the ReCiPe impact assessment method and was not applied in this LCA (Huijbregts et al., 2016).

The results in the SOD category can only be compared with Ross et al. (2009) and Ross et al. (2004), who investigated the impact of the launch of APCP and UDMH fuelled rockets. Other studies investigating ozone depletion are available, but they are investigating the effect of specific launchers, so that their results cannot be compared with this LCA (AE Jones et al., 1995; NASA, 1995). The LCA performed here yielded the result, that the combustion of APCP has the largest impact on the ozone layer, followed by UDMH, which is on par with the findings of Ross et al. (2004) and Ross et al. (2009). However, while they found that UDMH fuelled rockets cause 66 to 90 times less ozone depletion than APCP fuelled rockets, this LCA pointed towards UDMH causing 1000 times less ozone depletion. This difference is likely to be caused by a combination of an underestimation of the ODP of NO and the exclusion of the impact of H_2O done in this LCA. Therefore, it can be concluded that the results of this LCA agree with previous research, although a quantitative comparison is not possible due to different methodologies.

In line with Ross et al. (2010) and Ross et al. (2009), this study shows the considerable sensitivity of the global impacts of rocket launches towards the annual launch rate. The global warming impact associated with launch activities is currently insignificant, as also recognized by the industry (Murray et al., 2013). Although they were causing the emission of 0.79 Mt CO_2-eq. in 2019, this is representing only 0.0016% of the global greenhouse gas emissions in 2010 (IPCC, 2014). However, due to the projected increase of the launch-related emissions in the coming decades, it cannot be excluded, that climate change mitigation measures become necessary on the way to a net-carbon neutral world, by banning propellants with a high GW impact, which was also highlighted by Ross and Vedda (2018). The impact forecast of the development of SOD showed that the launch activities in 2019 caused an ozone depletion impact of 1.1 kt CFC-11-eq., which corresponds to 0.39% of the global emissions of ozone depleting substances in 2019 (Hegglin, Fahey, McFarland, Montzka, & Nash, 2015). This result highlights that the global SOD impact caused by rocket launches is more significant than their GW impact. Considering the further projected decrease in the global emissions of ozone depleting substances following the Montreal protocol, and the increase of the launch related SOD to 6.38 kt CFC-11-eq. in 2050, this share is expected to grow significantly in the coming decades (WMO, 2018).

5.2. Limitations of the study

An LCA is only as good as the data it is relying on. The data quality and the assumptions made during the data collection of this exploratory LCA of rocket launches are the biggest limitations of this study. Therefore, this study should not be interpreted as a stable assessment of the propellants, but more be regarded as a first step to performing an accurate LCA of rocket launches. Although every LCA is subjected to these limitations in some way and although it was tried to minimize the number of assumptions and value choices, are the emissions of propellants not well understood enough to consider this LCA to be accurate (Dallas et al., 2020; Hauschild et al., 2018). Such data quality concerns arise from the adopted inventories of Pettersen et al. (2016), the LCI compiled for the launch and the adopted CFs. Pettersen et al. (2016) discussed the quality of their data in detail in their report. This discussion is therefore focusing on the LCI of the launch stage and the LCIA. However, an inaccuracy was introduced by applying their inventories to the conduction of the impact forecast. The results presented in this study are not necessarily representative for rocket launches from other spaceports as their inventories were compiled specifically for launches from French Guiana. However, the major source of influence is not stemming from the transport of the propellant to the French territory, but more from the electricity mix on French Guiana, which is influencing the impact of all fuelling and waste treatment processes, as well as of the generation of LOx, and LH_2 from methanol. French Guiana has a high share of 64% renewables in its electricity mix, which lowers the GW impact arising from processes at the launch site (Pettersen et al., 2016). The GW impact arising from the production of propellants is therefore likely underestimated in the impact forecast, as all the major spacefaring countries have a significantly lower share of renewable energy in their electricity mix (Enerdata, 2019). However, a detailed regionalized study was beyond the scope of this work.

The exclusion of afterburning from the launch LCI is skewing the results, as it is likely that under oxidized combustion products like H, CO, O and OH continue to react after exiting the nozzle to form CO_2 and H_2O, both of which having a lower GWP (Bennett & McDonald, 1998). An investigation of the extent of afterburning influencing the results was beyond the scope of this study, however looking at Figure 5a and 5b, its inclusion is not deemed to influence the results measurably as the sensitivity of the scores towards the GWPs of H, CO, O and OH are small.

A further limitation was the lack of standardized GWPs for the NTCFs and ODPs for the compounds emitted by the rockets. This is a limitation shared with the scientific community working on an LCA on aviation (Jungbluth & Meili, 2019). As the current approach of multiplying the GW impact of CO_2 with a factor, in order to indirectly include the effects of emitted NTCFs, was deemed too inaccurate for this LCA, GWPs were adopted from other scientific work and ODPs were estimated (Jungbluth & Meili, 2019). This induces additional uncertainty in the LCA, which was incorporated by choosing large standard deviations for the Monte-Carlo simulation. As Figure 5a and 5b show, the uncertainty in in the adopted GWPs of BC and the alumina particulates, as well as the uncertainty in the ODPs of NO and HCl have the largest impact on the final results and are the main cause for the large standard deviation. There is no consensus about the GW impact of BC (Table 2), however a conservative GWP of BC was assumed here. A further uncertainty stems from CEARUN not calculating the amount of BC emitted, so that the real BC production rate during the combustion of hydrocarbons is still unknown (Simmons, 2000). The real warming impact from RP-1 is therefore likely underestimated. There is also no consensus about the GWP of alumina particulates. Although the IPCC (2013) has concluded that brightly coloured particles, such as alumina, have a cooling effect on the climate, Ross and Sheaffer (2014) have found the alumina particulates to have a warming impact, as they absorb upwelling longwave radiation. However, they stated the poor understanding of the impact of alumina in the stratosphere, calling for further research on this topic, which did not happen to this date. The assumption of the IPCC (2013), that brightly coloured particulates like alumina particles have a cooling effect on the climate was followed in this study. If further research proved the warming impact of alumina particulates, APCP would also have a significant warming impact on the climate, caused by its BC and alumina emissions. Therefore, the impact forecast would also show a higher global GW impact of the rocket launches, as the dampening effect of the solid propellant would disappear. However, it is unlikely, that the GW impact from rocket launches poses a threat to successful climate change mitigation, due to its low impact on a global scale.

Further limitations towards the validity of the calculated SOD impacts stem from the omission of the ozone depleting effect of H, O, H_2O and alumina particulates pointed out by Ross et al. (2009). As these authors stated that the impacts of these emissions are likely to be small compared to NO, Cl and HCl, this omission is justified, considering the inability to estimate ODPs for them. It must be kept in mind, that the launch of rockets fuelled by RP-1, LH_2, and LCH_4 is affecting the ozone layer, despite this LCA not reflecting this impact. Furthermore, are the estimates of the ODPs of Cl and HCl highly uncertain, due to the chosen approach of estimating them through the chlorine content. These affect the accuracy of the calculated SOD impacts, however it is deemed as unlikely, that the conclusions from this study change because of this rough estimation.

Despite these shortcomings, this LCA is sophisticated enough to compare the propellants relative to each other and to highlight the importance of employing a life cycle perspective, as the results of the uncertainty assessment show. A similar approach was used for the impact forecast. It was not designed to paint an accurate picture of the future development of the rocket-propellant related global warming impact, but more to deliver an outlook of the effects of the trends present in that market. The general conclusions from the forecast can therefore be trusted, albeit the specific values and shares cannot.

5.3. Policy implications

This study highlights the important differences of the environmental performance of the studied propellants. Its findings can be used to reduce the carbon footprint of rocket launches. The two most suitable propellants for achieving this are LH_2 and LCH_4 since their combustion has the least impact on the ozone layer and the climate. Future rockets should therefore be relying on one of these two propellants to minimize their GW impact. Although LCH_4 requires significantly less energy for its production than LH_2 and therefore has a lower GW impact, it is, as of now, still an unproven propellant, since no methane-fuelled rocket has ever flown. LH_2, on the other hand, is already a reliable and clean rocket propellant, although its production is causing a large impact on the climate and the ozone layer. The environmental performance of its production processes can easily be optimised by using renewable energy, thereby reducing its GW impact. From an environmental perspective is LCH_4 currently the most suited propellant and its use should be prioritised in next-generation rockets, assuming no BC is produced during its combustion. Although the use of LH_2 and LCH_4 is projected to increase in the future (Figure 6a), RP-1 is expected to dominate the launch market mainly related to the activities of SpaceX, which wants to increase the number of RP-1 fuelled Falcon 9 and Falcon Heavy launches to from 9 to 60 and 2 to 10, respectively, by 2023 (Federal Aviation Administration [FAA], 2020). The GW impact of the space industry rises significantly if SpaceX succeeds with this drastic increase of the launch rate. This could be avoided if a focus is instead being placed on the use of LH_2 or LCH_4.

The results of this study also show that the current impact of the space industry on GW is indeed small, justifying the perception in the industry, that its environmental impacts are of little concern (Murray et al., 2013). However, the current contribution to SOD is already significant, with rocket launches causing 0.39% of the global emissions of ozone depleting substances. Both impacts are projected to increase in the future, if the launch industry evolves along the pathway assumed in this study. Due to the projected dominance of RP-1 as a rocket propellant will the share of the production at the GW impact decrease. But while the emissions occurring during the production can be mitigated by using renewable energy, the impact of the launch emissions of the propellants cannot be reduced without switching to a less impactful propellant. The global SOD impact will also rise significantly, due to the increasing use of APCP. This could lead to mitigating measures becoming enforced by policymakers, in order to protect the ozone layer.

The use of RP-1, UDMH and APCP has to be avoided, to ensure that the space launch market is not limited in its growth for environmental reasons, The next generation of rockets being developed should therefore be relying either on LH_2 or LCH_4.

5.4. Further research

A validation of the results presented here is desirable in future studies. The quality of the results of CEARUN should be compared against real emission data or with more sophisticated models. The influence of afterburning on the results should also be investigated. Furthermore, the quality of the LCIA could be improved by calculating GWPs of the NTCFs based on a common set of assumptions using atmospheric models. This could be done using the Community Earth System Model, which was applied by Sherwood et al. (2018) to calculate the GWP of water vapour. Special consideration should be given to the calculation of the GWPs of the alumina particulates and BC, as these influence the scoring of the propellants the most. The same approach can be applied for uncovering the ODPs of not only the three chemicals investigated here, but also of the other emissions. The results presented here could furthermore be improved by conducting an LCA of the propellants where the impacts of the emissions at different altitudes is investigated. The study of Fuglestvedt et al. (2010) points towards emissions generally having a larger impact when emitted at high altitudes. This could be incorporated by calculating and applying altitude dependent CFs. Thus, the GW impact of global rocket launches could be calculated more accurately. The impact forecast developed here could be improved by performing a scenario analysis on how the rocket launch sector might develop in the future, which could further highlight policy recommendations.

6. Conclusion

The first analysis of the entire life cycle of the rocket propellants RP-1, LH_2, LCH_4, UDMH and APCP using LCA was conducted. The two investigated impact categories were global warming and stratospheric ozone destruction. UDMH was found to have the largest global warming impact, followed by LH_2 and RP-1. LCH_4 is associated with the lowest impact on the climate, while the use of APCP was found to have a cooling impact. The emissions released during the launch have a negligible contribution to the impact score of LH_2, LCH_4 and UDMH, but black carbon emissions dominate the global warming impact of RP-1. The emission of alumina particles from APCP is causing its cooling impact. The effect of other emissions, especially CO_2, was found to be insignificant, as also uncovered in other studies (Dallas et al., 2020; Ross & Sheaffer, 2014). Careful consideration is necessary when judging the impact of APCP, since the effect of alumina emissions remains uncertain (Dallas et al., 2020; IPCC, 2013; Ross & Sheaffer, 2014). The assessment of the ozone depletion impact of the propellants' combustion showed that APCP has the largest impact followed by UDMH. The emissions of other propellants were found to have no impact, while the production of rocket propellants was generally found to have no significant ozone depleting impact.

The application of LCA and the widening of its scope to include the production of the propellants and their combustion during the launch proved to eradicate the misconception, that LH_2 and UDMH are clean propellants (Ross & Sheaffer, 2014). They were shown to have the largest GW impact, despite their combustion having a low impact on the climate, due to the large energy use during their production. This highlights the need for a life cycle perspective when assessing the environmental impacts of propellants, similar to other products (Dallas et al., 2020). The possibility to optimise the GW impact of the production of UDMH is limited, as much of it is caused by direct emissions during waste treatment. The GW impact of LH_2 can be easily optimised by using renewable energy in its production. This would make it the most desirable propellant from an environmental perspective, as no carbon is emitted during the launch. As the effect of such improvements was not investigated, methane is seen as the most promising propellant, since its production requires little energy and it is releasing only minor greenhouse gases when combusted. APCP should not be used as a propellant in orbital rockets as it is causing the release of significant amounts of ozone depleting substances.

The impact forecast yielded the result, that the largest share of the climate change impact of the rocket launches in 2019 is caused by the emissions released during the production of propellants. This highlights the possibility to achieve significant emission reductions by optimising the environmental performance of the production processes and thereby lowering the carbon footprint of launch activities considerably. With UDMH being phased out and RP-1 becoming the dominantly used rocket propellant, the share of the production at the GW impact and therefore the optimisation potential will decrease. Global rocket launches are currently not posing a threat to successful climate change mitigation due to their low impact on a global scale. However, due to the projected growth of the number of annual launches and RP-1 becoming the dominantly used propellant, the GW impact will rise significantly, so that climate change mitigation measures might become necessary in the future. This also applies to the impact of rocket launches on the ozone layer. The launch activities in 2019 caused 0.39% of the global emissions of ozone depleting substances, almost exclusively caused by the combustion of APCP. This share is expected to increase in the future, as the global emissions of ozone depleting substances are reduced, and the number of rocket launches is increasing. The use of APCP should therefore be regulated to protect the ozone layer. From an environmental perspective are LH_2 and LCH_4 therefore seen as the least problematic propellants.

Our understanding of the environmental impacts of rocket emissions remains limited, especially considering the impact of BC and alumina emissions in the stratosphere (Dallas et al., 2020; Ross & Sheaffer, 2014). Similar to Murray et al. (2013), Ross and Vedda (2018) and, the author of this study calls for continued research into the atmospheric impacts of rocket emissions, to not only improve this LCA, but also to prove that the exclusion of rocket launches from current climate change mitigation and ozone layer recovery efforts is justified (Maury et al., 2020).

Acknowledgements

I thank my academic supervisor, Assoc. Prof. Johan Berg Pettersen for his guidance and support over the last year. Furthermore, I want to express my gratitude to my co-supervisor, Assoc. Prof. Noora Partamies for her valuable insight on stratospheric ozone depletion. I especially thank my family, girlfriend and friends for their support their feedback and for generally helping me through my studies.

Appendix

A1. Comparison of the LCI with other sources

Depicted in Figure A1 is the LCI used in this LCA and its comparison with the alternative modelling program RP-A, the composition assumed by Ross and Sheaffer (2014) and data from Simmons (2000). The emission inventory compiled using CEARUN, is overall agreeing well with Simmons (2000). Major differences only arise from CEARUN predicting a higher share of under oxidized emission species (CO and Cl). However, these differences might have arisen from measurement errors made when adopting the data from the figures presented in Simmons (2000). Furthermore did Simmons (2000) not include OH and BC emissions in his work, which additionally causes differences in the exhaust composition. The results of RP-A deviate slightly from the LCI. RP-A generally predicts more CO_2 and less CO emissions than CEARUN. RP-A did also not include the emission of OH. CEARUN was therefore delivering the most complete inventory and its result were therefore used as the foundation of the LCI. It can be seen, that the compositions assumed by Ross and Sheaffer (2014) have major gaps, considering that they only included CO_2, H_2O, alumina and BC emissions. They are thereby missing important climate forcers, like CO, H, OH and underestimate the amount of alumina emitted from APCP significantly.

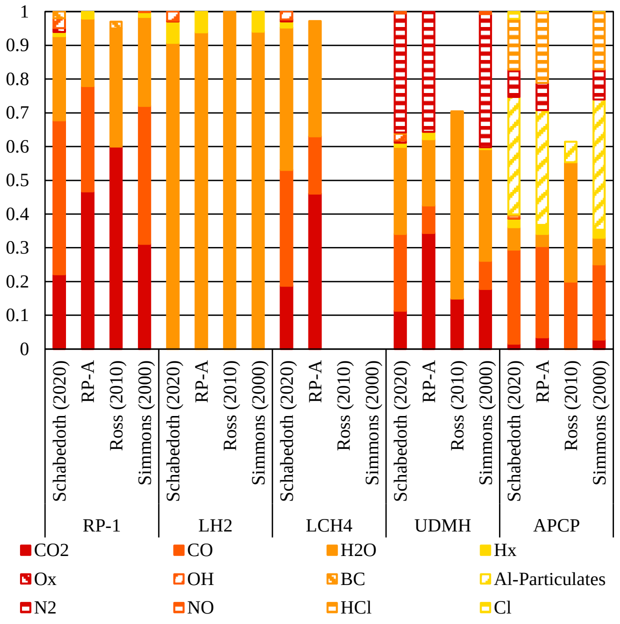

Figure A1 – Comparison of the LCI used in this LCA with the results of an analysis using RP-A, the emission composition assumed by Ross and Sheaffer (2014) and data from Simmons (2000). Emissions are shown in kg per kg propellant combusted.

A2. On the adapted IPAT-equation

The adapted IPAT-equation outlined in Section 3.4 calls for the definition of three variables: The number of annual rocket launches $n(t)$, the consumption of each propellant p during an average rocket launch over time, $PC(p,t)$, and the GW and SOD impact per kg of propellant p. The number of annual rocket launches was assumed based on data from the European Space Policy Institute (ESPI, 2020) and Fortune Business Insights (2020). The ESPI gave data on the annual number of rocket launches between 2000 and 2019, and the report by Fortune Business Insights discussed the future economic growth of the global launch service market between 2019 and 2026. Assuming a fixed ratio between the economic size of the launch service market in 2019 and the number of rocket launches in that year, a projection for the number of launches between 2020 and 2026 was achieved, as outlined in Figure A2**.** Assuming an exponential regression function, the number of launches in 2050 is expected to increase to 590. Then, a second-degree polynomial regression was conducted to estimate the amount of launches in the years 2027 until 2049 to establish a full time series for the number of rocket launches between 2019 and 2050.

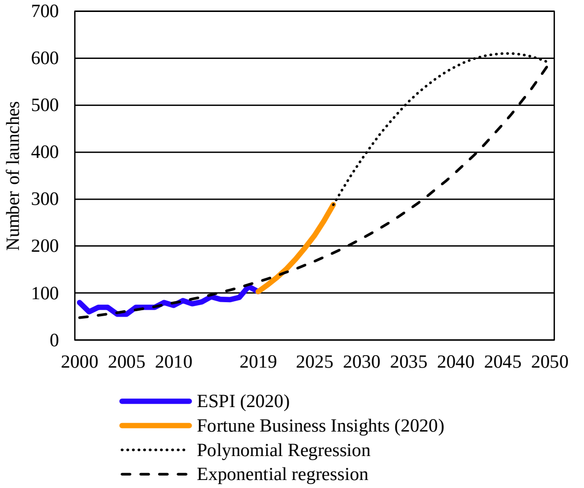

Figure A2 – Annual global launch rate over the modelling timeframe. Historic launch rates are adopted from ESPI (2020).

No data on the propellant consumption of the average rocket launch over time was available. The propellant consumption was estimated in the following way: The average propellant consumption of a rocket launch in the year 2019 was calculated by summing up the propellants consumed in each rocket launch in that year and dividing it by the number of launches. The number of launches and the respective rockets were given by the ESPI (2020). The number of launches and the respective fuel consumption per rocket are outlined in Table A1. The average rocket launch in 2019 was found to consume and burn 145 tons of RP-1, 27 tons of LH$_2$, 106 tons of UDMH and 56 tons of APCP.

The future development of the average propellant consumption was based on different trends in the industry. These trends were judged on whether they influence the use of each propellant positively or negatively, followed by a subjective, relative assessment of the strength of each influence, expressed with a ranking from 1 for a weak influence to 4 for a strong influence, as illustrated in Table A2. A ranking of 1 was assumed to increase the use of the propellant with 0.5% per year, whereas a ranking of 4 induces an increase or decrease of 2%. Only UDMH was exempted from this approach, as the propellant was expected to be phased out by 2031. These changes were summed to estimate the development of the propellant consumption over time. LCH$_4$ is introduced as a propellant with the introduction of the Starship in 2021 (Henry, 2019). The launch of one Starship consumes 3700 t of LCH$_4$, which influences the average consumption of LCH$_4$ per launch significantly (Kyle, 2020). The average launch in 2021 was therefore assumed to consume 45 t of LCH$_4$, growing according to the described approach.

As can be seen from Figure A3, the average use of RP-1, LH$_2$ and LCH$_4$ will increase significantly in the coming decades, due to the introduction of several large rocket using these propellants. The use of UDMH is expected to decrease sharply, related to this fuel being phased out by 2031, mainly because it is severely toxic (Dallas et al., 2020). The average use of APCP is growing slightly over the modelling timeframe, as the growth induced by the introduction of large rockets using solid boosters is somewhat negated by the likely use of APCP in small and launchers, which reduces the average use of this propellant per rocket launch (Dallas et al., 2020).

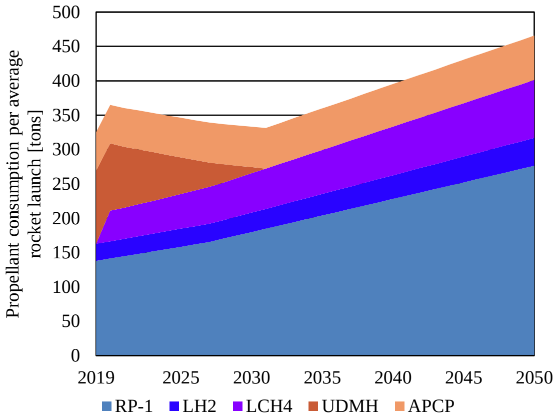

Figure A3 – Development of $\mathrm{PC}(\mathrm{p}, \mathrm{t})$ over the modelling timeframe.

Table A1 – Overview over the rocket launches in 2019 and their fuel use.

Launcher	Launches in 2019	Propellant mass [t]					Source
		RP-1	LH2	LCH4	UDMH	APCP	
Antares 230	2	242				13	Kyle (n.d.-a)
Ariane 5	4		170			480	Arianespace (2016)
Atlas V 500	2	284	21			213	United Launch Alliance (2010)
Long March 6[a]	1	91					Weidong, Chang, and Wei (2019)
Long March 11[a]	3					51	Harvey (2019)
Long March 2C[a]	1				228		China Academy of Launch Vehicle Technology (2016a)
Long March 3C	1		18		297		China Great Wall Industry Corporation (n.d.)
Long March 4B	6				249		Harvey (2019)
Long March 5	1	608	181				(Kyle, n.d. -a)
Long March 3B	10		18		402		China Academy of Launch Vehicle Technology (2016b)
Delta 4	2		231			178	United Launch Alliance (2013)
Delta 4 Heavy	1		639				United Launch Alliance (2013)
Electron	6	13					Kyle (n.d.-d)
Epsilon	1					84	Japanese Aerospace Exploration Agency (2018)
Falcon 9	9	484					Kyle (2017)
Falcon Heavy	2	1330					Kyle (2019)
GSLV	1		28		110	410	Indian Space Research Organisation (n.d.)
H-2B	1		194			264	Japanese Aerospace Exploration Agency (n.d.)
Hyperbola-1	1					36	iSpace (n.d.)
Jielong 1[a]	1					20	Yiming (2019)
Kuaizhou[a]	5					26	Harvey (2019)
Pegasus XL	1					20	Kyle (n.d.-b)
Proton	5				632		International Launch Services (n.d.-a, n.d.-b)
PSLV	5				41	225	Kyle (n.d.-c)
Rockot	2				87		Kyle (n.d.-e)
Soyuz 2-1	16	272					Arianespace (2012)
Vega	1					122	Arianespace (2014)

[a] Propellant mass was not available and was estimated to amount for 87% of the gross mass of the rocket, similar to the Ariane 5's mass breakdown (Maury et al., 2020).

Table A2 – Overview over the industry trends

Propellant	Influence	Source	Positive / Negative	Starting from	Strength of influence
RP-1	Planned upscaling of the launch rate of the Falcon 9 and Falcon Heavy.	FAA (2020)	Positive	2020	2
	Introduction of Irtysh and Angara	ITAR-TASS News Agency (2019a, 2019b); Kyle (n.d. -b)	Positive	2020	2
	Introduction of the Long March 9	Andrew Jones (2018); Xinhua News Agency (2018)	Positive	2028	
	Cheap and easy to produce	Dallas et al. (2020)	Positive	2020	1
LH_2	Introduction of the SLS	FAA (2018; 2020)	Positive	2021	2
	Introduction of the Long March 9	Andrew Jones (2018); Xinhua News Agency (2018)	Positive	2028	2
	High I_{sp} makes it attractive to use in the future	Dallas et al. (2020)	Positive	2028	1
LCH_4	Introduction of the Starship	Henry (2019)	Positive	2021	3
	Introduction of New Glenn	Blue Origin (n.d.)	Positive	2021	2
	High I_{sp}, cheap	Pettersen et al. (2016)	Positive	2020	1
UDMH	Replacement of the Proton, Rockot until 2030	Harvey (2019)	Negative	2020	-9
	Phasing out of UDMH fuelled Chinese until 2030	Harvey (2019)	Negative	2020	-9
	Industry trend towards green propellants	Gohardani et al. (2014)	Negative	2020	-2
APCP	Introduction of the SLS and Ariane 6	ESA (n.d.); FAA (2018); Foust (2020)	Positive	2020	2
	APCP is suitable for small launchers	Dallas et al. (2020)	Negative	2020	-1

REFERENCES

Arianespace. (2012). Soyuz User's Manual Issue 2 Revision 0.

Arianespace. (2014). Vega User's Manual Issue 4 Revision 0.

Arianespace. (2016). Ariane 5 User's Manual.

Bennett, R., & McDonald, A. (1998). *Recent activities and studies on the environmental impacts of rocket effluents.* Paper presented at the 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Cleveland, USA.

Blue Origin. (n.d.). New Glenn. Retrieved from https://www.blueorigin.com/new-glenn/

Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., . . . Koch, D. (2013). Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres, 118*(11), 5380-5552.

Bond, T. C., Zarzycki, C., Flanner, M., & Koch, D. (2011). Quantifying immediate radiative forcing by black carbon and organic matter with the Specific Forcing Pulse. *Atmospheric Chemistry and Physics, 11*(4), 1505-1525.

Byers, M., & Byers, C. (2017). Toxic splash: Russian rocket stages dropped in Arctic waters raise health, environmental and legal concerns. *Polar Record, 53*(6), 580-591.

Chanoine, A. (2017). *Environmental impacts of launchers and space missions.* Paper presented at the Clean Space Industrial Days, Noordwijk, Netherlands.

Chertow, M. R. (2000). The IPAT equation and its variants. *Journal of Industrial Ecology, 4*(4), 13-29.

China Academy of Launch Vehicle Technology. (2016a). LM-2C Series Launch Vehicle. Retrieved from http://calt.spacechina.com/n840/c5344/content.html

China Academy of Launch Vehicle Technology. (2016b). LM-3A Series Launch Vehicle. Retrieved from http://calt.spacechina.com/n840/c5348/content.html

China Great Wall Industry Corporation. (n.d.). LM-3C. Retrieved from http://cgwic.com/Launchservice/LM2C.html

Dallas, J., Raval, S., Gaitan, J. A., Saydam, S., & Dempster, A. (2020). The environmental impact of emissions from space launches: A comprehensive review. *Journal of Cleaner Production, 255*, 120209.

Daniel, J. S., & Solomon, S. (1998). On the climate forcing of carbon monoxide. *Journal of Geophysical Research: Atmospheres, 103*(D11), 13249-13260.

Daniels, S. L. (1989). Products of incomplete combustion (Ox, COx, HOx, NOx, SOx ROx, MOx and POx). *Journal of hazardous materials, 22*(2), 161-173.

Danilin, M. Y., Ko, M. K., & Weisenstein, D. K. (2001). Global implications of ozone loss in a space shuttle wake. *Journal of Geophysical Research: Atmospheres, 106*(D4), 3591-3601.

De Santis, M., Urbano, G., Blengini, G. A., Zah, R., Gmuender, S., & Ciroth, A. (2013). *Environmental impact assessment of space sector: LCA results and applied methodology*. Paper presented at the 4th CEAS Air & Space conference, Linköping, Sweden.

de Vries, W., Kros, J., Reinds, G. J., & Butterbach-Bahl, K. (2011). Quantifying impacts of nitrogen use in European agriculture on global warming potential. *Current Opinion in Environmental Sustainability, 3*(5), 291-302.

Derwent, R. (2018). Hydrogen for heating: Atmospheric impacts. A literature review.

Derwent, R., Collins, W., Johnson, C., & Stevenson, D. (2001). Transient behaviour of tropospheric ozone precursors in a global 3-D CTM and their indirect greenhouse effects. *Climatic Change, 49*(4), 463-487.

Enerdata. (2019). Share of renewables in electricity production. Retrieved from https://yearbook.enerdata.net/renewables/renewable-in-electricity-production-share.html

European Space Agency. (2017). Prometheus to power future launchers. Retrieved from https://www.esa.int/Enabling_Support/Space_Transportation/Prometheus_to_power_future_launchers

European Space Agency. (n.d.). Ariane 6. Retrieved from https://www.esa.int/Enabling_Support/Space_Transportation/Launch_vehicles/Ariane_6

European Space Policy Institute. (2020). *ESPI Yearbook 2019 - Space policies, issues and trends.* Vienna, Austria: ESPI.

Federal Aviation Administration. (2018). *The Annual Compendium of Commercial Space Transportation: 2018*. Washington D.C., USA: United States Government Publishing Office.

Federal Aviation Administration. (2020). *Draft Environmental Assessment for SpaceX Falcon Launches at Kennedy Space Center and Cape Canaveral Air Force Station*.

Fortune Business Insights. (2020). Space Launch Services Market Size, Share & Industry Analysis, By Payload (Satellite, Stratollite, Cargo, Human Spacecraft and Testing Probes) By Orbit (LEO, MEO, GEO and Beyond GEO), By Launch Platform (Land, Air, and Sea), y Vehicle Type (small Lift Launch Vehicle, Medium-to-HEavy Lift Launch Vehicles), By End User (Commerical, and Military & Government) and Regional Forecast, 2019-2026. Retrieved from https://www.fortunebusinessinsights.com/industry-reports/space-launch-services-market-101931

Foust, J. (2020). First SLS launch now expected in second half of 2021. *Spacenews.* Retrieved from https://spacenews.com/first-sls-launch-now-expected-in-second-half-of-2021/

Fuglestvedt, J. S., Shine, K. P., Berntsen, T., Cook, J., Lee, D. S., Stenke, A., . . . Waitz, I. A. (2010). Transport impacts on atmosphere and climate: Metrics. *Atmospheric Environment, 44*(37), 4648-4677. doi:https://doi.org/10.1016/j.atmosenv.2009.04.044

Gallice, A., Maury, T., & del Olmo, E. (2018). *Environmental impact of the exploitation of the Ariane 6 launcher system.* Paper presented at the Cleanspace Industrial Days 2018, Amsterdam, Netherlands.

Gohardani, A. S., Stanojev, J., Demairé, A., Anflo, K., Persson, M., Wingborg, N., & Nilsson, C. (2014). Green space propulsion: Opportunities and prospects. *Progress in Aerospace Sciences, 71*, 128-149.

Harvey, B. (2019). *China in Space*. Cham, Switzerland: Springer Nature.

Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (2018). *Life Cycle Assessment : Theory and Practice* (1st ed.). Cham, Switzerland: Springer International Publishing.

Hegglin, M. I., Fahey, D. W., McFarland, M., Montzka, S. A., & Nash, E. R. (2015). *Twenty Questions and Answers About the Ozone Layer: 2014 Update-Scientific Assessment of Ozone Depletion: 2014*.

Henry, C. (2019). SpaceX targets 2021 on commercial Starship launch. *SpaceNews.* Retrieved from https://spacenews.com/spacex-targets-2021-commercial-starship-launch/

Hinkle, C., & Knott III, W. (1985). *A Summary of Environmental Effects of Space Shuttle Launches at the John F. Kennedy Space Center, Florida After the First 24 Launches*. Paper presented at the 152nd Annual Meeting of the American Association for the Advancement of Science, Philadelphia, USA.

Huijbregts, M., Steinmann, Z., Elshout, P., Stam, G., Verones, F., Vieira, M., . . . Van Zelm, R. (2016). *ReCiPe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level Report I: Characterization*.

Indian Space Research Organisation. (n.d.). GSLV Mk III. Retrieved from https://www.isro.gov.in/launchers/gslv-mk-iii

Intergovernmental Panel on Climate Change. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories , Prepared by the National Greenhouse Gas Inventories Programme* (H. S. Eggleston, L. Buendia, K. Miwa, T. Ngara, & K. Tanabe Eds.). Japan: IGES.

Intergovernmental Panel on Climate Change. (2013). *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change* (T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley Eds. Vol. 1535). Cambridge, UK and New York, USA: Cambridge University Press.

Intergovernmental Panel on Climate Change. (2014). *Climate Change 2014: Mitigation of climate change, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (O. Edenhofer, P.-M. R, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, & J. C. Minx Eds.). Cambridge, UK: Cambridge University Press.

International Launch Services. (n.d.-a). Proton 1st and 2nd Stage. Retrieved from https://www.ilslaunch.com/proton-1st-and-2nd-stage/

International Launch Services. (n.d.-b). Proton 3rd Stage. Retrieved from https://www.ilslaunch.com/proton-3rd-stage/

International Organization for Standardization. (2006a). ISO 14040:2006(E): Environmental management - Life cycle assessment - Principles and framework.

International Organization for Standardization. (2006b). ISO 14044:2006(E): Environmental management - Life cycle assessment - Requirements and guidelines.

iSpace. (n.d.). Hyperbola-1 User Manual.

ITAR-TASS News Agency. (2019a). Prototypes of Russia's Soyuz-5 space rocket components to be ready in 2020 — designer. Retrieved from https://tass.com/science/1077002

ITAR-TASS News Agency. (2019b). Russia to launch new Angara carrier rocket in 2020. Retrieved from https://tass.com/science/1102539

Japanese Aerospace Exploration Agency. (2018). Epsilon Launch Vehicle User's Manual

Japanese Aerospace Exploration Agency. (n.d.). About H-IIB Launch Vehicle. Retrieved from https://global.jaxa.jp/projects/rockets/h2b/

Jones, A. (2018). China reveals details for super-heavy-lift Long March 9 and reusable Long March 8 rockets. *Spacenews.* Retrieved from https://spacenews.com/china-reveals-details-for-super-heavy-lift-long-march-9-and-reusable-long-march-8-rockets/

Jones, A., Bekki, S., & Pyle, J. (1995). On the atmospheric impact of launching the Ariane 5 rocket. *Journal of Geophysical Research: Atmospheres, 100*(D8), 16651-16660.

Jungbluth, N., & Meili, C. (2019). Recommendations for calculation of the global warming potential of aviation including the radiative forcing index. *The International Journal of Life Cycle Assessment, 24*(3), 404-411.

Klöpffer, W., & Grahl, B. (2014). *Life cycle assessment : a guide to best practice*. Weinheim an der Bergstrasse, Germany: Wiley.

Kyle, E. (2017). Space Launch Report: SpaceX Falcon 9 Data Sheet. Retrieved from https://www.spacelaunchreport.com/falcon9.html

Kyle, E. (2019). Space Launch Report: SpaceX Falcon Heavy. Retrieved from https://www.spacelaunchreport.com/falconH.html

Kyle, E. (2020). Space Launch Report: Super Heavy/Starship Data Sheet. Retrieved from http://spacelaunchreport.com/bfr.html

Kyle, E. (n.d.-a). Space Launch Report: Antares (Taurus II). Retrieved from https://www.spacelaunchreport.com/taurus2.html

Kyle, E. (n.d.-b). Space Launch Report: Pegasus Data Sheet. Retrieved from https://www.spacelaunchreport.com/pegasus.html

Kyle, E. (n.d.-c). Space Launch Report: PSLV. Retrieved from http://www.spacelaunchreport.com/pslv.html

Kyle, E. (n.d.-d). Space Launch Report: Rocket Lab Electron Data Sheet. Retrieved from https://www.spacelaunchreport.com/electron.html

Kyle, E. (n.d.-e). Space Launch Report: Rokot/Strela. Retrieved from https://www.spacelaunchreport.com/rokot.html

Kyle, E. (n.d. -a). Space Launch Report: CZ-5-7 Data Sheet. Retrieved from http://www.spacelaunchreport.com/cz5.html

Kyle, E. (n.d. -b). Space Launch Report: New Launchers - Angara. Retrieved from https://www.spacelaunchreport.com/angara.html

Larson, E. J., Portmann, R. W., Rosenlof, K. H., Fahey, D. W., Daniel, J. S., & Ross, M. N. (2017). Global atmospheric response to emissions from a proposed reusable space launch system. *Earth's Future, 5*(1), 37-48.

Lund, M. T., Aamaas, B., Berntsen, T. K., Bock, L., Burkhardt, U., Fuglestvedt, J. S., & Shine, K. P. (2017). Emission metrics for quantifying regional climate impacts of aviation. *Earth System Dynamics, 8*(3), 547-563.

Maury, T., Loubet, P., Serrano, S. M., Gallice, A., & Sonnemann, G. (2020). Application of environmental life cycle assessment (LCA) within the space sector: A state of the art. *Acta Astronautica, 170*, 122-135. doi:https://doi.org/10.1016/j.actaastro.2020.01.035

McBride, B. J., & Sanford, G. (1996). Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications. In. Washington D.C., USA: U.S. National Aeronautics and Space Administration.

Molina, M. J., Molina, L. T., Zhang, R., Meads, R. F., & Spencer, D. D. (1997). The reaction of ClONO2 with HCl on aluminum oxide. *Geophysical Research Letters, 24*(13), 1619-1622.

Murray, N., Bekki, S., Toumi, R., & Soares, T. (2013). On the uncertainties in assessing the atmospheric effects of launchers. *Progress in Propulsion Physics, 4*, 671-688. doi:10.1051/eucass/201304671

National Aeronautics and Space Administration. (1995). *Final Environmental Impact Statement for the Cassini Mission*.

Pempie, P., Vernin, H., & Entreprises, A. (2015). *Multi Purposes Reusable LOX/CH4 Bleed Rocket Engine*. Paper presented at the 7th European Conference for Aeronautics and Space Sciences, Milano, Italy.

Pettersen, J. B., Silva, E. J., Bergsdal, H., & Solli, C. (2016). *D3.3 Environmental impact of space propellants - final version*. Retrieved from European Space Agency

Ponomarenko, A. (2010). RPA: Tool for Liquid Propellant Rocket Engine Analysis C++ Implementation.

PRÉ. (2020). SimaPro. Retrieved from https://simapro.com/

Preuss, A., Preclik, D., Mading, C., Gorgen, J., Soller, S., Haidn, O., . . . Sender, J. (2008). *LOx/Methane technology efforts for future liquid rocket engines*. Paper presented at the 5th International Spacecraft Propulsion Conference, Heraklion, Greece.

Ross, M., Danilin, M., Weisenstein, D., & Ko, M. K. (2004). Ozone depletion caused by NO and H2O emissions from hydrazine‐fueled rockets. *Journal of Geophysical Research: Atmospheres, 109*(D21).

Ross, M., Mills, M., & Toohey, D. (2010). Potential climate impact of black carbon emitted by rockets. *Geophysical Research Letters, 37*(24).

Ross, M., & Sheaffer, P. (2014). Radiative forcing caused by rocket engine emissions. *Earth's Future, 2*(4), 177-196.

Ross, M., Toohey, D., Peinemann, M., & Ross, P. (2009). Limits on the Space Launch Market Related to Stratospheric Ozone Depletion. *Astropolitics, 7*(1), 50-82. doi:10.1080/14777620902768867

Ross, M., & Vedda, J. A. (2018). The policy and science of rocket emissions.

Saltelli, A., Tarantola, S., Campolongo, F., & Ratto, M. (2004). *Sensitivity analysis in practice : a guide to assessing scientific models*. Chichester, UK: Wiley.

Sherwood, S. C., Dixit, V., & Salomez, C. (2018). The global warming potential of near-surface emitted water vapour. *Environmental Research Letters, 13*(10), 104006.

Shindell, D., & Faluvegi, G. (2009). Climate response to regional radiative forcing during the twentieth century. *Nature Geoscience, 2*(4), 294-300.

Simmons, F. (2000). *Rocket exhaust plume phenomenology*: American Institute of Aeronautics and Astronautics.

SpaceX. (n.d.). Starship. Retrieved from https://www.spacex.com/starship

Turner, M. J. L. (2009). *Rocket and Spacecraft Propulsion : Principles, Practice and New Developments* (3rd ed.). Berlin, Germany: Springer.

United Launch Alliance. (2010). Atlas V Launch Services User's Guide.

United Launch Alliance. (2013). Delta IV Launch Services User's Guide.

Varela, J. R. (n.d.). Simulación 4.0. Retrieved from https://ucema.edu.ar/~jvarela/index_eng.htm

Varghese, T., & Krishnamurthy, V. (2017). *The chemistry and technology of solid rocket propellants (a treatise on solid propellants)*: Allied Publishers.

Weidema, B., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., . . . Wernet, G. (2013). Overview and methodology. In *Data quality guideline for the ecoinvent database version* (Vol. 3, pp. 1).

Weidong, Z., Chang, L., & Wei, W. (2019). Innovation and Outlook of the New Generation of Cryogenic and Quick-Launch Launch Vehicle. *中国航天 (英文版), 18*(2), 3-12.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment, 21*(9), 1218-1230.

World Meteorological Organization. (2018). *Scientific Assessment of Ozone Depletion: 2018*. Geneva, Switzerland: World Meteorological Organization.

Xinhua News Agency. (2018). China to launch Long March-9 rocket in 2028 Retrieved from http://www.xinhuanet.com/english/2018-09/19/c_137477227.htm

Yiming, G. (2019). Jielong 1 Debut Flight Achieved Success. *中国航天 (英文版), 20*(3), 53-53.

NTNU
Norwegian University of
Science and Technology