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Comparison Study on the Environmental Impact of Different Launcher Architectures

Jan-Steffen Fischer[1†], *Stefanos Fasoulas*[1], *Céline Brun-Buisson*[2], *Dr. Encarna del Olmo*[2]
[1] *University of Stuttgart, Institute of Space Systems, Pfaffenwaldring 31, 70569 Stuttgart, Germany*
fischerj@irs.uni-stuttgart.de · fasoulas@irs.uni-stuttgart.de
[2] *ArianeGroup SAS, 51-61 Route de Verneuil 78130 Les Mureaux Cedex France*
celine.brun-buisson@ariane.group · encarna.delolmo@ariane.group
†Corresponding author

Abstract

Space flight is at a turning point in history. On the one hand, more space systems are being launched than ever before. This trend will continue in the coming years due to the increased interest in satellite constellations and space exploration. On the other hand, spaceflight in Europe is facing the challenge of reducing its environmental impact. A significant part of this impact is caused by production, which is analyzed in this study.

This paper is the first scientific publication that analyzes the production of launchers with respect to the absolute impact as well as the share of subsystems. In addition, different launcher system architectures and propellants are compared for the first time in order to provide recommendations for the environmentally friendly development of launcher systems. The methodology presented for calculating the environmental impact of launchers during the design phase is therefore a novelty.

For this purpose, generic environmental indicators developed on Ariane 6 version A64 production provided by ArianeGroup are used. These data were determined for all important subsystems to enable a comparison between different launcher architectures. The study defines different typical target orbits, staging concepts and propellants as a framework for this study. In the following step, different launcher architectures are designed using common design formulas and subsystem mass distribution. Finally, their environmental impact is then estimated using 19 indicators. In the final step, a detailed analysis of the share of subsystem and manufacturing processes is made as well as a comparison of different launcher architectures and propellant systems for one ton of payload into a different orbit.

1. Introduction

For over 80 years, humankind has been able to send rockets into space. Since then, space travel has developed into a field of activity for states and, increasingly, commercial companies. While satellites have so far mainly been used as individual systems or in small numbers to network the world, enable navigation and earth observation, future constellations will raise the number of objects in space as well as the number of launches to a new order of magnitude.[1] In 2022, a new record of space launches was set, which is only the beginning of a new era in which space launches will become commonplace.

At the same time, mankind faces the challenge to consider the limits of Earth and to change its actions to a sustainable way.[2] Against this background, space industry is also asked to analyze its processes in terms of environmental impact and, where necessary, to change them. Regulatory changes such as the European Union's Green Deal encompass all sectors and support this transformation.[3] Space industry's high level of innovation can also serve as a model for other industries in many areas. Even though spacecraft, once launched into space, no longer have a direct impact on Earth, their production, launch, and re-entry involve emissions to the atmosphere and environmental impacts that affect Earth. A significant share of this is accounted for by the production of launch vehicles and their propellants.[4]

This comparative study is therefore taking a closer look at the environmental impact of launcher production. For this purpose, a cooperation with ArianeGroup was carried out, which estimated environmental indicators based on a life cycle assessment (LCA) of the production of Ariane 6[5] and provided them to the University of Stuttgart as generic data per subsystem. Based on this data, a stage optimization is done for different orbits considering typical propellants and launcher architectures. Subsytem masses are estimated using literature and internal values. Based on the calculated data, the environmental impact of production is calculated using data provided by ArianeGroup. The study thus enables

for the first time a scientific evaluation of the total impact of launcher production regarding 19 environmental indicators as well as the share of the main subsystems and process steps.
Furthermore, different launcher architectures are then compared with each other regarding one ton of payload into a specific orbit to analyze the influence of key parameters and the choice of propellant on the environmental impact. Based on this results, recommendations are given for the development of environmentally friendly launchers.

2. Theory

2.1 Life cycle assessment

Life cycle assessment is an ISO-standardized quantitative method that allows the environmental impact of products and processes to be calculated.[6,7] LCA according to these norms consists of four steps. First, the goal and scope definition. In the second step, the life cycle inventory analysis, consists of data collection and calculation to quantify relevant inputs and outputs in the life cycle of the product. The third step, impact assessment, is defined by the calculation of the impact in different categories and their allocation. Finally, the interpretation of results is the last step, where evaluation, sensitivity and consistency check as well as conclusions take place.
The European Commission has been developing a uniform LCA methodology for the European Economic Area since 2013 with a recommendation for Product Environmental Footprint ((EU)2021/2279). The aim is to introduce a methodology for determining the environmental impact of products sector by sector. The methodology comprises 16 environmental indicators (see table 3), which are based on existing scientific factors. In the long term, sustainability criteria will also be introduced for the space activities of the European Union (e.g. Copernicus, Galileo, IRIS^2).[8]
European Space Agency (ESA) developed a LCA methodology since 2012 on the basis of international standards.[9–12] ESA's method is described in the "Space System Life Cycle Assessment (LCA) Guidelines",[13] which can be obtained from ESA on request. These guidelines define the classification into individual project phases and subsystems. Furthermore, relevant environmental impact categories are introduced, which are based on existing common LCA calculation methods (see Tab. 3), and a database is provided on contract which gives general data about the production of different subsystems, which will be used for this study regarding the propellant production.
Only a few studies have been conducted on the production of rockets. ArianeGroup was the pioneer with the LCA of Ariane 5[10] and Ariane 6[5] and it up to today the only company which published their results. Neumann,[14] Miraux[15] and Calabuig[16] published LCA studies which considered production focusing on the reuse of launch vehicles. However, no absolute values based on existing launcher systems have been published to date.

2.2 Stage optimization

In the following, the launch vehicle design by stage optimization will be explained in more detail, which is the basis of this study. For this purpose, first the Tsiolkovsky equation for a multistage system is given as[17]

$$\Delta v = \sum_{i=1}^{n} c_{e,i} \ln\left(\frac{1}{\sigma_i + \frac{\mu_{i+1}}{\mu_i}}\right). \tag{1}$$

Δv = total velocity achieved by launcher c_{ei} = effective exit velocity of i-th stage [m/s] σ_i = structural factor of i-th stage [-] (Ratio of the structural mass of a substage $m_{s,i}$ to the launch mass of the sub-stage $m_{0,i}$) μ_i = relative mass of i-th stage [-] (ratio of a sub-rocket launch mass $m_{0,i}$ to the total launch mass m_0) and rearranged with respect to the payload ratio $\mu_{n+1} = \mu_p$ to

$$\mu_p = \left(\frac{\mu_1}{\mu_1\sigma_1 + \mu_2}\right)^{\frac{c_{e,1}}{c_{e,2}}} e^{\frac{-\Delta V}{c_{e,2}}} \mu_2 - \mu_2\sigma_2. \tag{2}$$

Subsequently, the equation can be derived in order to calculate the zeros (i.e. maxima of μ_p). For two-stage systems, this results in,

$$\frac{\delta\mu_p}{\delta\mu_2} = f(\mu_2, ...) = 0. \tag{3}$$

For three-stage systems respectively, this results in

$$\mu_p = \left(\frac{\mu_2}{\mu_2\sigma_2 + \mu_3}\right)^{\frac{c_{e,2}}{c_{e,3}}} \left(\frac{\mu_1}{\mu_1\sigma_1 + \mu_2}\right)^{\frac{c_{e,1}}{c_{e,3}}} e^{\frac{-\Delta V}{c_{e,3}}} \mu_3 - \mu_3\sigma_3 \tag{4}$$

and

$$\frac{\delta\mu_p}{\delta\mu_2\delta\mu_3} = f(\mu_2, \mu_3, ...) = 0. \tag{5}$$

respectively.

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3. Methodology

The following chapter describes the logic used to calculate the environmental impact. Fig. 1 shows the procedure for this. In the following the single steps are described in detail.

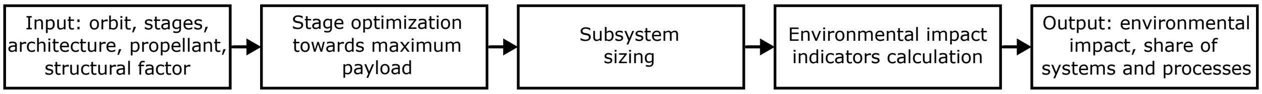

Figure 1: Logic of the calculation process used for this study

3.1 Input

3.1.1 Target orbits

The different launcher architectures are examined for the typical orbits and payloads shown in Tab. 1. Low earth orbit (LEO), Medium earth orbit (MEO), Geostationary transfer orbit (GTO), Trans-Lunar-Orbit-Insertion (TLI), and Trans-Mars-Orbit-Insertion (TMI) are examined in the study. LEO is used for many missions, especially Earth observation missions as well as constellations. MEO is used maninly for navigation. GTO missions are typically used for communication satellites. A Trans Lunar Orbit Insertion as well as Trans Mars Orbit Insertion are used for future manned as well as unmanned exploration missions. The transport capacities differ according to the categories of small, medium, heavy and super-heavy launchers. A normalized value of 1 ton into a given orbit is therefore defined as the functional unit. The study method allows, as a simplification, to multiply linearly the given values for an orbit for higher payload masses.

Table 1: Reference target orbits and their Δv considered for this study.

Orbit	Δv [km/s]
LEO	9
MEO	10
GTO	11.6
TLI	12
TMI	15

Table 2: Typical propellant combinations and their effective velocity c_e and ratio oxidizer to fuel ROF and density ρ used in this study

Propellant	$c_{e,SL}$ [m/s]	$c_{e,VAC}$ [m/s]	ROF	ρ [kg/m^3]
LOX/LH2	3050	4400	6.03	1141/70.85
LOX/CH4	3200	3550	3.6	1141/422.8
LOX/RP-1	3050	3425	2.56	1141/807.5
NTO/UDMH	2500	2950	2.14	1442/793
NTO/MMH	N/A	3100	2.14	1442/880
Solid	2750	2900	N/A	1810

3.1.2 Propellant combinations

The design of the stages is based on possible combinations of fuels, which is shown in Tab. 2. This corresponds to the common propellant combinations that currently represent most rocket launches. Liquid oxygen (LOX)/liquid hydrogen (LH2) engines use cryogenic hydrogen and oxygen and therefore require specially insulated tanks. Due to the low density of hydrogen, large tank volumes and correspondingly high structural masses are required. They are currently used as the core stage on the Ariane 5 and the SLS, among others. Liquid methane (CH4) and liquid oxygen engines will be used much more frequently in the future. Several engines (Prometheus, Raptor, BE-4) are currently under development. Liquid oxygen with kerosene (RP-1) has been in use since the beginning of space flight and is used, for example, on Soyuz and Falcon 9, among others. Hydrazine-based core stages with unsymmetrical dimethylhydrazine (UDMH) as fuel and Dinitrogen tetroxide (NTO) as an oxidizer are hypergolic and used on Long March 2 and 4, among others other mainly Chinese launchers. Solid propellants (based on Ammonium perchlorate, Aluminium and HTPB or PBAN) are used as boosters and core stages, for example in Ariane 5, SLS and Vega rockets.

3.1.3 Stages and launcher architecture

In this study, different staging concepts regarding number of stages and architecture will be investigated. Basically, a distinction is made between tandem and parallel staging. Tandem staging is characterized by the stacking of the different stages. Parallel staging is often used with boosters, which are attached to the outside of the core stage and run parallel to it. Both types of staging concepts are considered in this study. For this purpose, the staging concepts

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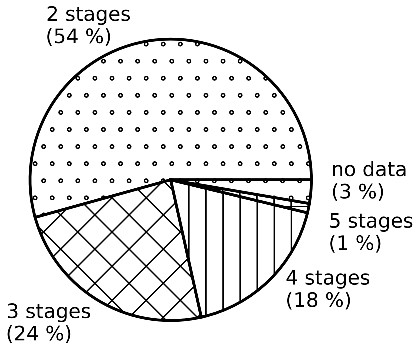

Figure 2: Number and share of staging concepts of rockets launched in 2022

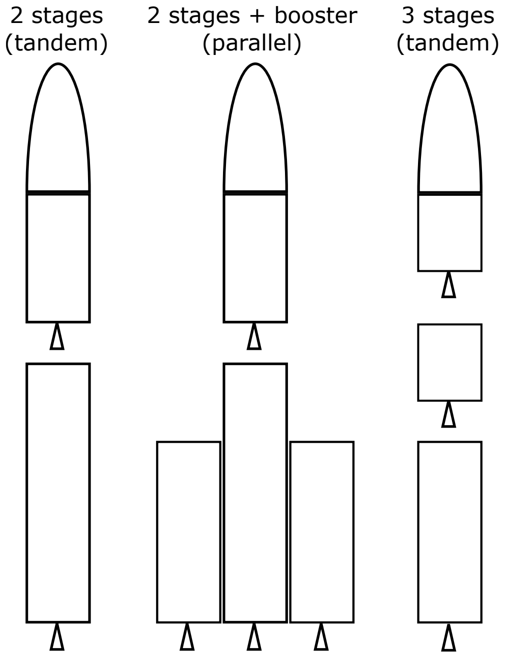

Figure 3: Staging concepts considered in this study

used in 2022 will first be analyzed. Boosters are counted hereby as a single stage added. In Fig. 2, the proportions are shown. More than half of the launched rockets used two-stage systems (98 % thereof in tandem staging). Another close quarter used three-stage systems (58 % in tandem staging, 42 % in parallel staging). 4 or 5 stages were used less than 20 % (all of them with parallel staging)). No data were available for 3 % of the launchers. Therefore, about 80 % of global launches in 2022 used 2- or 3-stage systems.

3.2 Stage optimization

For a four-stage system, the equations presented in Sec. 2.2 can no longer be solved analytically, so this study focuses on 2- and 3-stage systems, which accounts for most of the rockets launched in 2022. 3-stage systems are analyzed both, for tandem and parallel staging (2 stages + booster) in the first stage (see Fig. 3). To determine the maximum possible payload ratio, a stage optimization algorithm is used, which theoretical background was described in Sec. 2.2. Using the formulas determined there and the input values from Sec. 3.1, the stage optimization is now performed by maximizing Eq. 2 or 4. For this a python script is used, which determines the maximum value by means of the *scipy.optimize.minimize* function. The outputs are the values for μ_p, μ_2 and for systems with booster or a third stage additionally μ_3.

3.3 Subsystem sizing

The values calculated in the stage optimization can now be used to dimension the subsystems. For this purpose, the total mass of the launcher architecture is first calculated using the calculated μ_p and the total mass of the stages is calculated using μ_2 or μ_3. For 2-stage systems with booster, μ_2 represent the system mass distribution after separation of the boosters. With the given structural masses, the dry mass and propellant masses can be calculated. Using the given ROF and ρ of the propellants, the volume v of the tanks can be calculated. For the other subsystems, the data from Fig. 4 are taken for upper, and lower stages, respectively. For the mass distribution of the boosters and upper parts as well as subsystems not covered by the literature, data from ArianeGroup is used. The required thrust was estimated using the total mass and an acceleration factor of 1.1 at takeoff.

3.4 Environmental impact indicator calculation

With the calculated subsystem masses, volumes, and thrust, respectively, the environmental indicators can now be determined using the generic environmental indicators determined by ArianeGroup. For this purpose, the characteristic size of the subsystem (m^3, kg or kN) is multiplied by the generic data and then added for the overall system.

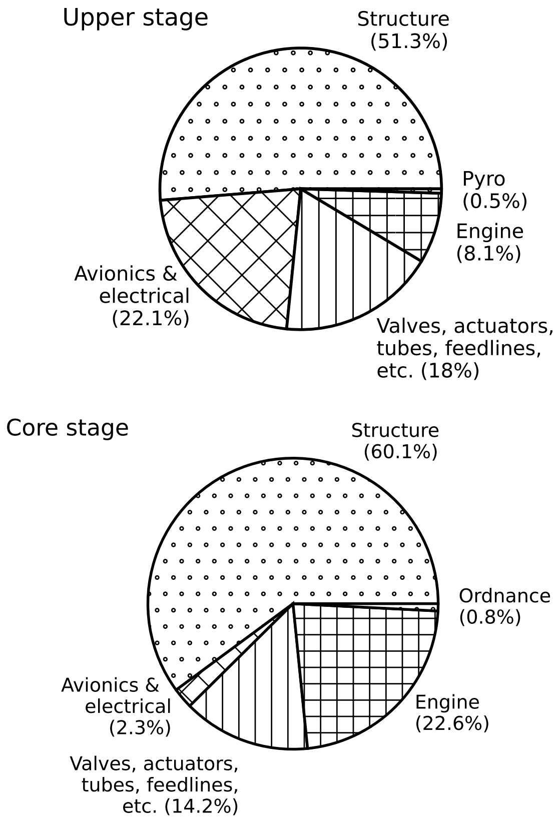

Figure 4: Subsystem weight distribution for core and upper stage[18]

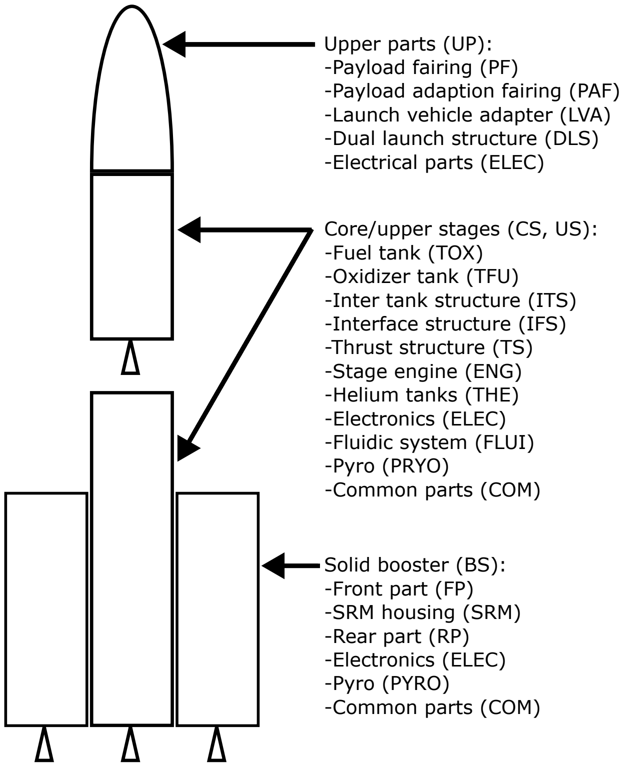

Figure 5: Considered stages and subsystems for environmental data with their abbreviation

3.4.1 Environmental indicators

For this study, an updated version of the ESA LCA methodology is used, which includes the PEF environmental indicators. The environmental indicators are shown in Tab. 3 with the corresponding units, abbreviation and calculation methodology. The ESA indicators *Abiotic resource depletion potential (metal and mineral resources)* are not included in the reserve-based calculation method, as the ultimate-reserve-based method of the PEF is used here. Furthermore, the *Gross Water Consumption Potential* and *Metal depletion potential* were not considered, since *Water use* and *Abiotic resource depletion potential (metal and mineral resources)* are already calculated. The floating indicators Al_2O_3 *particle emissions*, *Mass left in space*, *Mass disposed in ocean* are not relevant for the production and were therefore not considered in the study.

3.4.2 Ariane 6 version A64 production and propellant environmental data

Ariane 6 is the new European launcher, which consists of an oxygen-hydrogen propulsion system in the core and upper stages. The rocket is offered in two versions, A62 with 2 and A64 with 4 solid propellant boosters.[19] ArianeGroup conducted a life cycle assessment for the Ariane 6 version A64 launcher during development with a first iteration in 2018, followed by a second one in 2020. The Study of ArianeGroup was considering manufacturing of products, assembly, integration and testing (AIT) in Europe, lauch campaign before the flight and launcher final AIT in Kourou. Not considered are the research and development phase, office work, business trips, payload activites as well as infrastructure.[5]

Environmental indicators were determined in a cooperation between ArianeGroup and the University of Stuttgart for the subsystems of the core and upper stage and booster as well as payload structure. For this purpose, the values of the Ariane 6 LCA study conducted by ArianeGroup were taken and calculated to a respective characteristic value (per kg, kN or m3) for the subsystems shown in Fig. 5. The data on core and upper stage consists of an individual dataset of oxidizer tank, fuel tank, intertank structure, interstage structure, thrust frame, engine, helium tank, fluidic system, electronics, pyro and common parts.

Table 3: Environmental indicators used in this study.

Environmental indicator	ESA[13]	PEF[20]	Abbreviation	Unit	Calculation Method
Global warming potential (100 y)	X	X	GWP	kg CO2 eq.	IPCC2013[21]
Ozone depletion potential	X	X	ODP	kg CFC-11 eq.	WMO 2014[22]
Human toxicity potential, cancer	X	X	HTPC	CTUh	USEtox model 2.1[23]
Human toxicity potential, non-cancer	X	X	HTPNC	CTUh	USEtox model 2.1[23]
Abiotic resource depletion potential (metal and mineral resources)		X	ARDPM	kg Sb eq.	CML 2002 (ultimate reserve)[24]
Abiotic resource depletion potential (fossil fuels)	X	X	ARDPF	MJ	CML 2002[24]
Photochemical ozone formation potential	X	X	POFP	kg NMVOC eq.	ReCiPe 2008[25]
Particulate matter formation potential	X	X	PMF	Disease incidence	PM UNEP 2016[26]
Freshwater eutrophication potential	X	X	FEUP	kg P eq.	ReCiPe[27]
Marine eutrophication potential	X	X	MEUP	kg N eq.	ReCiPe[27]
Terrestrial eutrophication potencial		X	TEUP	mol N eq.	Accumulated exceedance[28]
Ionising radiation potential	X	X	IRP	kBq U 235 eq.	Frischknecht et al., 2000[29]
Freshwater ecotoxicity potential	X	X	FETP	CTUe	USEtox model 2.1[23]
Marine ecotoxicity potential	X		METP	kg 1,4-DB eq.	CML 2002[30]
Air acidification potential (PEF)		X	AAP1	mol H+ eq.	Accumulated exceedance[28]
Air acidification potential (ESA)	X		AAP2	kg SO2 eq.	CML 2002[30]
Land use		X	LU	- (Points)	LANCA[31]
Water use		X	WU	m3 world eq.	AWARE[32]
Primary Energy Consumption Potential	X		PRENE	MJ	ESA LCA 2020[13]

The solid boosters made out of a front part, solid rocket motor housing and rear part. The payload structure consisting of payload fairing, launch vehicle adapter, payload adaption fairing, launch vehicle adapter, dual launch system and electronics. The values only referred to production including acceptance tests and transport. Furthermore, data of the final assembly was delivered considering AIT of the payload structure on the upper stage and encapsulation, AIT of the core stage and boosters as well as final assembly of the launcher and fluidic consumption before launch. For the liquid fuels investigated in this study, the existing data sets of the ESA LCIA database are used.[13] These contain data on production, storage as well as transport and all necessary activities for fueling the launcher. For solid propellants, a generic data set from ArianeGroup was used, which includes raw materials, production, storage, transport and testing.

3.4.3 System boundaries

The system boundaries in this study are shown in Fig. 6. The study includes raw material extraction, production of subsystems at an industrial partner (IP), assembly, transportation and testing of the components at original equipment manufacturer (OEM) up to the finished stage. Further, the production, storage, and transportation of the propellants are considered. Finally, launch preparations and total system assembly are taken into account.

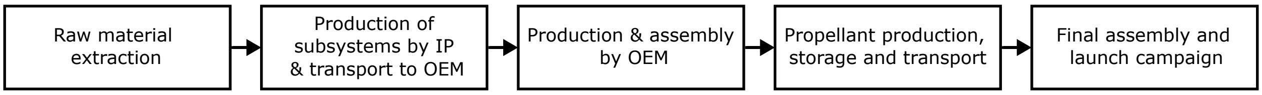

Figure 6: System boundaries considered in this study

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4. Results and discussion

4.1 Share of subsystems

As an example of how the individual subsystems contribute to the overall system, the example of a system consisting of core and upper stages and LOX/LH2 as propellant with solid boosters is analyzed here. For the structural factors, those of the Ariane 5 launcher are used ($\sigma_{cs} = 0.0207$, $\sigma_{bs} = 0.0772$, $\sigma_{us} = 0.048$).

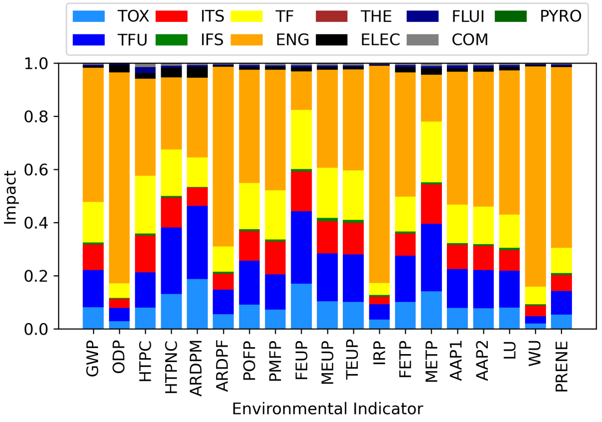

Figure 7: LOX/LH2 core stage system allocation

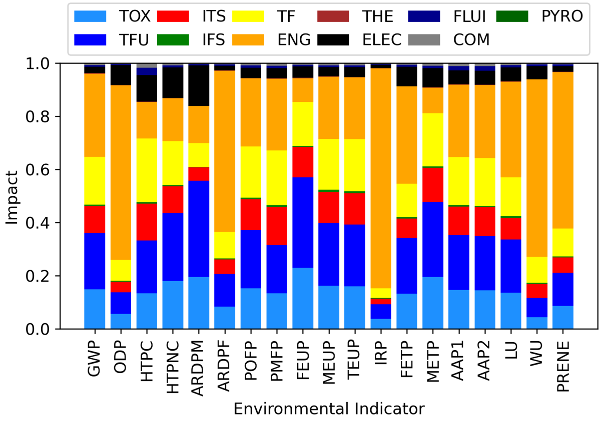

Figure 8: LOX/LH2 upper stage system allocation

The largest influence on the environmental impact of the core stage comes from the engine, thrust structure, inter-tank structure, as well as fuel tank and oxidizer tank (see Fig. 7). This affects all environmental indicators. For GWP, ODP, ARDPF, IRP, AAP1, AAP2, LU, WU and PRENE the engine has an influence > 50 %. This is primarily driven by the propellants required for testing the engine and the energy-intensive production compared to other subsystems. If testing is not considered, the impact of the engine is significantly reduced and is comparable to the other subsystems. Only for ARDPF, IRP, WU and PRENE the engine has then still an influence > 50 %. This can be similarly seen in the upper stage (see Fig. 8) with a higher influence from the electronic system. Furthermore, the engine hasn't a big influence compared to the core stage due to the lower engine mass fraction. It is noteworthy that the fuel tank has on average only 1.7 times the impact of the oxidizer tank, although it has 2.8 times the volume in both stages.

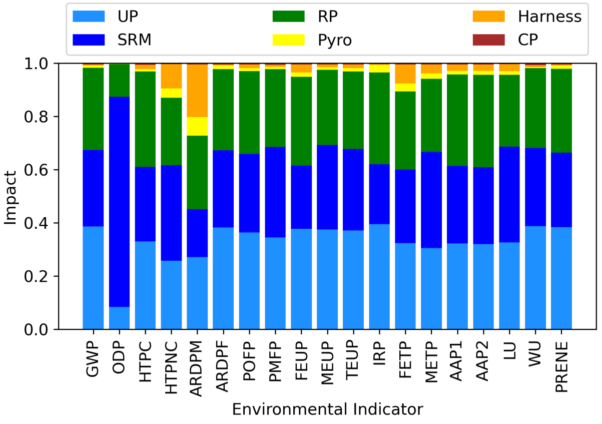

Figure 9: Solid booster stage system allocation

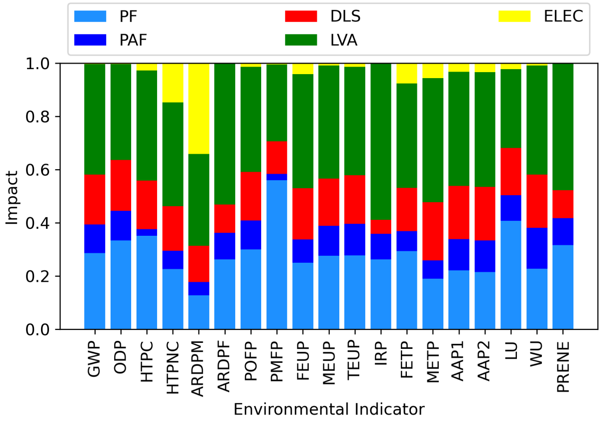

Figure 10: Upper part system allocation

The environmental influence of the booster is driven by the upper as well as the lower part and the SRM housing (see Fig. 9). The influence of the SRM housing on the ODP is remarkably high, as usually for carbon fibre structures. The harness influences ARDPM as well as HTPNC. The other subsystems are below 10 %. For the upper parts, the payload fairing as well as the launch vehicle adapter have the highest influence, followed by the dual launch system and payload adaption fairing (see Fig. 10). For ARDPM and HTPNC, the electronic system also has a major influence.

A look at the overall system in Fig. 11 also shows the share of production of the individual stages (CS, BS, US, UP), assembly (AL) as well as propellants (PCS, PUS, PBS). Here, a large influence of the propellants is noticeable. The influence of solid propellants (PBS) in particular is worth mentioning, which has on average an influence of a good third on the environmental indicators. Another factor is the propellant used in the core stage (PCS), which accounts for an average of 13 % of the environmental impact. In addition, there is a particularly high influence on WU and ODP. Overall, the propellants account for a good half of the environmental impact. The production of the core stage (CS, 20 % on average) and the booster (BS, 17 %) also have a major impact. In particular, this is higher for ARDPM than for the other environmental indicators, which can be explained by the metal consumption. The assembly (AL) contributes an average of 10 % to the environmental impact.

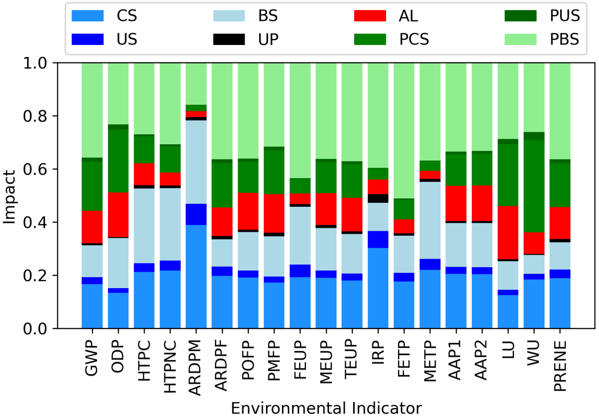

Figure 11: Total system allocation

4.2 Share of process steps

In the following, the production of the discussed system is analyzed in more detail. For this purpose, the given environmental data of the stage production is analyzed with regard to the process steps manufacturing, assembly, testing and transport. The propellants are evaluated in terms of production, storage, testing and transport.

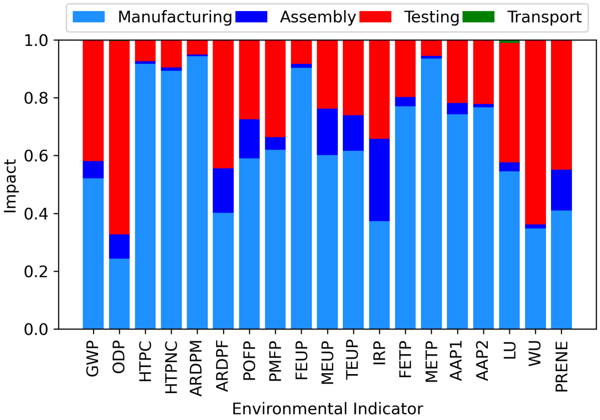

Figure 12: Core stage process allocation

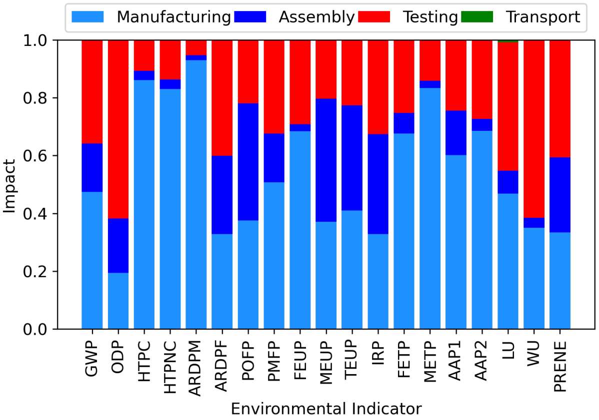

Figure 13: Upper stage process allocation

For the core stage, shown in Fig. 12, manufacturing (64 % on average) and testing (29 % on average, mainly driven by propellant consumption for engine test) has a major influence on all environmental indicators. Testing has an influence of over $>$ 50 % on ODP and WU. In third place is assembly, which has an influence $>$ 10 % on ARDPF, POFP,MEUP,TEUP,IRP and PRENE in particular. This is mainly driven by the electric consumption. For the production of the upper stage, shown in Fig. 13 the results are comparable with a higher influence of the assembly phase.
The environmental impact of production of the booster dry mass is primarily driven by manufacturing for all environmental indicators (see Fig. 14). Only for HTPNC, ARDPM and FETP the influence from transport is $>$ 10 %. For the production of the upper part, manufacturing also responsible for most of the environmental impact (see Fig. 14). Only for the environmental indicators IRP and PRENE does assembly have an influence $>$ 10 %. When considering the environmental impact of the entire production of dry mass, shown in Fig.16, the impact of manufacturing is on average at 45 % of environmental indicators, testing at 39 % and assembly at 14 %. Transport is responsible for only 2 % of the environmental impact on average. Testing is again driven by the consumption of propellants for engine testing. In propellant production, the manufacturing process itself is largely responsible for the environmental impact (see Fig.17). Only in the case of HTPB, HTPNC and LU does the storage of the propellant influence the environmental impact by $>$ 15 %.

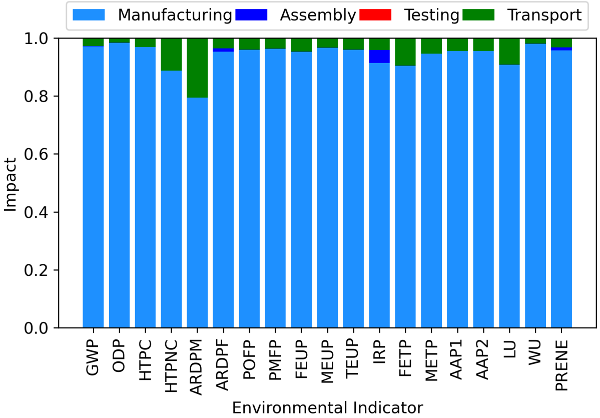

Figure 14: Booster stage process allocation

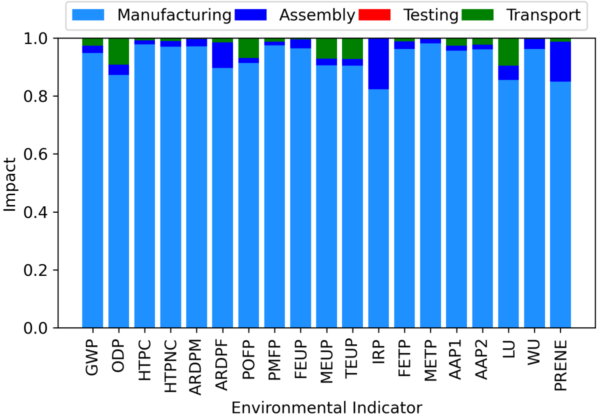

Figure 15: Upper part process allocation

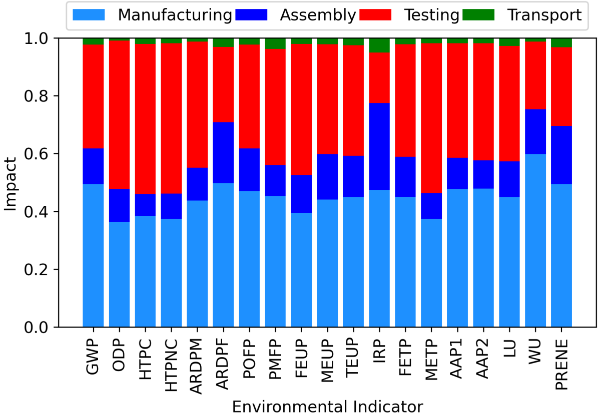

Figure 16: Dry mass process allocation

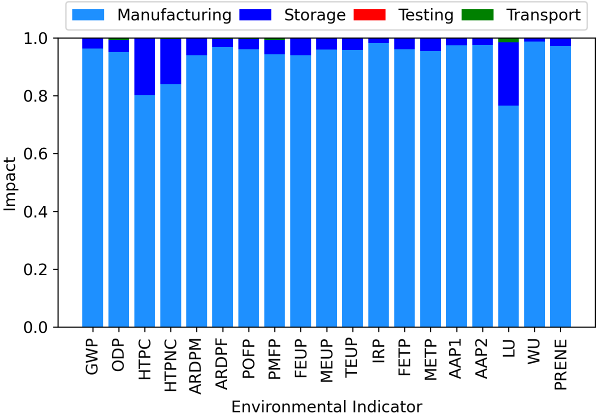

Figure 17: Propellant production process allocation

4.3 Comparison to normalization factors

In order to be able to compare the environmental impact of the production, references are used in the following for 1t payload into LEO by with a 2-stage system with LOX/LH2 propellant as well as solid booster, which was already analyzed in detail above. For the environmental indicators of the PEF method the normalization factors according to the EF 3.1 method are used.[20] These environemental indicators are given for the total environmental impact of a world population of 6,895,889,018 people for one year. Comparing this, the factors in Fig. 18 are calculated with the absolute values for the environmental indicators given in Tab. 4. It can be seen that for the FETP the highest influence comes with 291 persons equivalents. This is followed by ARDPF with 163, FEUP with 155, and ARDPM with 127 person equivalents. Remarkable are except AAP1 with 97 and HTPNC with 87 persons. For GWP, the production corresponds with 94 persons.

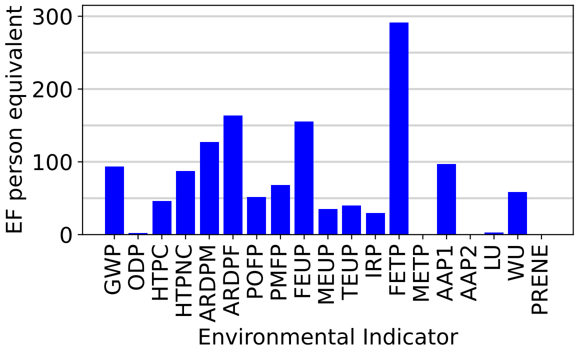

Figure 18: Comparison with EF normalization factors of the environmental impact of the production of a launcher for 1t into LEO

As a second comparison, the production of an electric car is given with 13.7 t CO2-eq.[33] The production of one launcher for 1 t payload into LEO would thus correspond to the production of about 52 cars. Since the environmental impact increases linearly with the payload, the values for a spacecraft with a payload of 150 t into LEO would have to be multiplied by a factor of 150 accordingly. In Tab.4 the absolute environmental indicators are given for different orbits.

Table 4: Environmental impact for different launcher architecture and propellant production for 1 t into orbit

Orbit	LEO	LEO	LEO	LEO	GTO	GTO	TLI	TLI
Stages	2+B	2	2	3	2	2	2	2
Oxidizer	LOX*	LOX	LOX	UDMH	LOX	LOX	LOX	LOX
Fuel	LH2*	RP-1	CH4	NTO	RP-1	CH4	RP-1	CH4
GWP	7.07E+05	2.64E+05	2.75E+05	3.97E+06	6.21E+05	6.26E+05	7.18E+05	7.17E+05
ODP	8.74E-02	3.23E-02	2.72E-02	8.96E-01	7.92E-02	6.33E-02	9.19E-02	7.27E-02
HTPC	7.96E-04	5.10E-04	5.25E-04	3.60E-03	1.23E-03	1.22E-03	1.43E-03	1.40E-03
HTPNC	1.12E-02	6.76E-03	6.97E-03	8.95E-02	1.62E-02	1.61E-02	1.88E-02	1.85E-02
ARDPM	8.09E+00	7.10E+00	7.00E+00	3.33E+01	1.65E+01	1.56E+01	1.91E+01	1.78E+01
ARDPF	1.06E+07	4.96E+06	4.61E+06	6.16E+07	1.16E+07	1.03E+07	1.34E+07	1.17E+07
POFP	2.11E+03	9.18E+02	8.78E+02	1.03E+04	2.18E+03	2.00E+03	2.53E+03	2.29E+03
PMFP	4.06E-02	1.75E-02	1.70E-02	1.77E-01	4.15E-02	3.87E-02	4.80E-02	4.43E-02
FEUP	2.49E+02	1.34E+02	1.37E+02	2.02E+03	3.09E+02	3.03E+02	3.56E+02	3.46E+02
MEUP	6.82E+02	2.99E+02	2.88E+02	5.80E+03	7.08E+02	6.51E+02	8.19E+02	7.45E+02
TEUP	6.98E+03	3.03E+03	2.92E+03	4.10E+04	7.21E+03	6.65E+03	8.34E+03	7.62E+03
IRP	1.26E+05	8.97E+04	8.20E+04	7.52E+05	2.02E+05	1.76E+05	2.32E+05	2.00E+05
FETP	1.65E+07	7.32E+06	7.00E+06	1.48E+08	1.73E+07	1.58E+07	2.00E+07	1.81E+07
METP	1.25E+09	6.64E+08	6.56E+08	6.05E+09	1.55E+09	1.47E+09	1.79E+09	1.68E+09
AAP1	5.39E+03	2.61E+03	2.47E+03	2.41E+04	6.25E+03	5.66E+03	7.24E+03	6.48E+03
AAP2	4.59E+03	2.25E+03	2.13E+03	1.99E+04	5.41E+03	4.88E+03	6.26E+03	5.60E+03
LU	2.46E+06	1.44E+06	1.51E+06	1.28E+07	3.58E+06	3.63E+06	4.16E+06	4.19E+06
WU	6.70E+05	7.62E+05	7.22E+05	2.37E+06	2.00E+06	1.81E+06	2.33E+06	2.10E+06
PRENE	1.31E+07	5.92E+06	5.52E+06	7.10E+07	1.38E+07	1.23E+07	1.60E+07	1.41E+07

*incl. propellants for engine test

4.4 Comparison of staging concepts

In the following, the different staging concepts will be examined. The environmental indicators are determined for the specified target orbits and the differences are discussed on the basis of the GWP. This environmental indicator is representative for all other indicators, since they behave in the same way.

In Fig. 19 - 22, the environmental impacts relative to the system with the highest impact are shown for the four selected fuel combinations. For the systems with LOX/RP-1, LOX/CH4 as well as LOX/LH2, the system with 2 stages and solid booster has the highest environmental impact for all orbits. For LOX/RP-1 and LOX/LH2, this is followed by the 3-stage system. For the LOX/CH4 system, the environmental impact of the 3-stage system is almost the same as that of the 2-stage system. For NTO/UDMH, it is different. Here, the 2-stage and 3-stage systems have nearly identical environmental impact for most orbits. However, this changes for the TMI, where the two-stage system has a higher environmental impact than the three-stage system. The two-stage system with boosters, on the other hand, has the lowest impact.

These results can be explained by the higher structural masses required for multistage systems. In addition, there is the influence of the boosters, which have a higher impact compared to RP-1, CH4 and LH2, especially due to the solid propellants used. Multi-stage systems are more optimal with respect to the required propellant. Empty structural mass is more often separated that no longer needs to be accelerated. This effect could lead to a similar result of the 2- and 3-stage system for LOX/CH4 system.

Furthermore, the use of a liquid booster instead of a solid fuel is investigated. For this purpose, the two systems for 1 t payload in the LEO were compared for the environmental indicators and shown in Fig. 23 and 24. It can be seen that for the LOX/LH2 system, a CH4 liquid booster would reduce the environmental impact to 87 % on average. Exceptions are HTPNC, ARDPM and WU, where the impact would even increase. For the CH4 system, the impact of switching to a liquid booster is more pronounced; on average, only 64 % of the environmental impact would still occur in production. However, WU and ARDPM is an exception. The latter, since more metal is needed for the booster and engine production.

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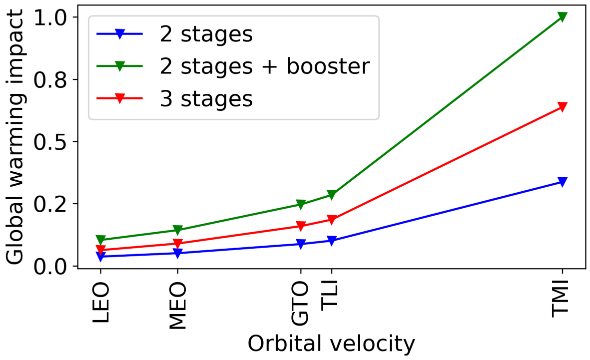

Figure 19: Comparison of LOX/RP-1 architectures

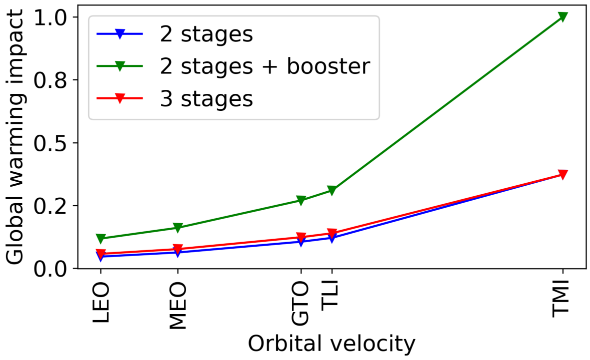

Figure 20: Comparison of LOX/CH4 architectures

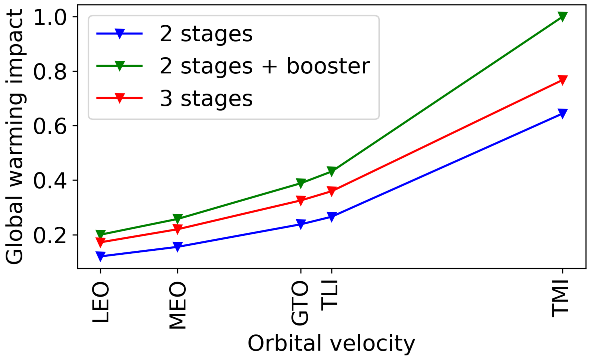

Figure 21: Comparison of LOX/LH2 architectures

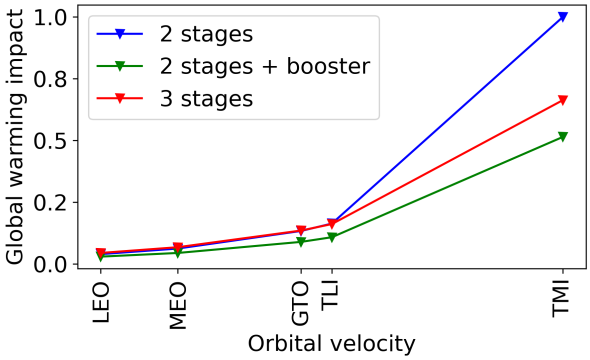

Figure 22: Comparison of NTO/UDMH architectures

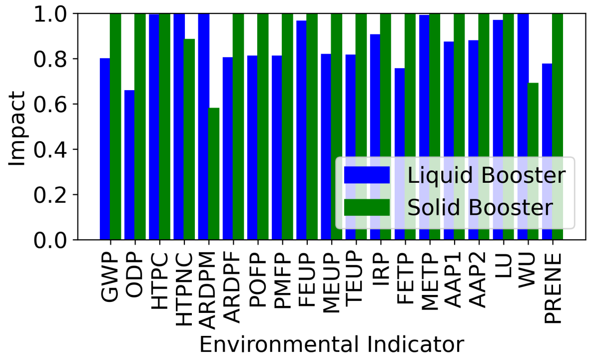

Figure 23: Comparison of solid vs. liquid CH4 booster for LOX/LH2 core and upper stage

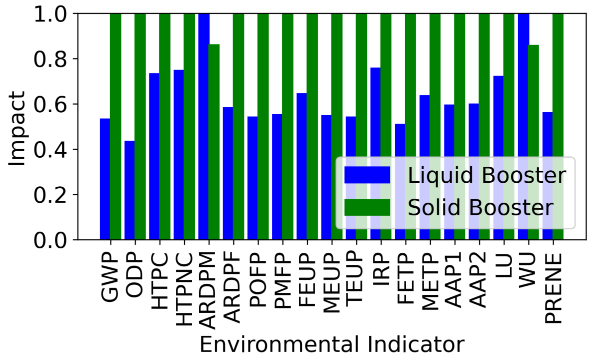

Figure 24: Comparison of solid vs. liquid CH4 booster for LOX/CH4 core and upper stage

4.5 Comparison of propellants

As a final comparison, the environmental impact of the different fuel systems will be compared for different orbits. For this purpose, first the 2-stage system is considered and compared for LEO in Fig. 25 and GEO in 26 for 1 t of payload. The comparison shows a clear difference between the fuels. NTO/UDMH has by far the largest environmental impact for both orbits. This is due to the particularly high impact of the fuels in all environmental indicators, which account for over 80 % in the total impact. In second place is the LOX/LH2 system, which has the second highest impact in 16 of the indicators. For the environmental indicators IRP and WU, LOX/RP-1 has the second highest impact. For HTPC, it is LOX/CH4. For GTO the situation is different, here LOX/RP-1 is second with 13 indicators. LOX/LH2 is in second place for GWP, ODP, ARDPF, PMFP and PRENE, LOX/CH4 has the lowest impact for all indicators.

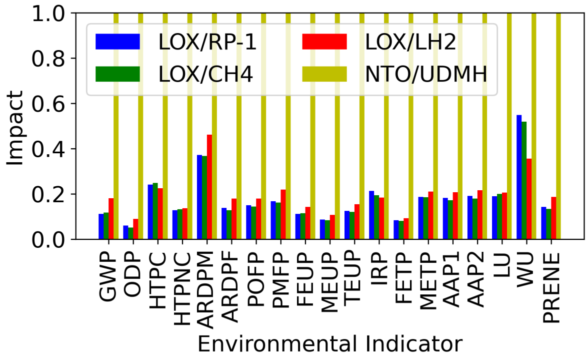

Figure 25: Comparison for 2 stages into LEO

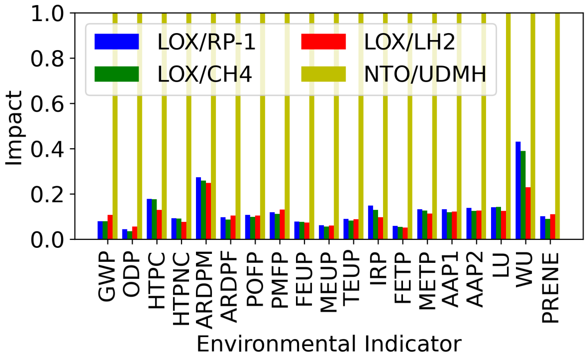

Figure 26: Comparison for 2 stages into GTO

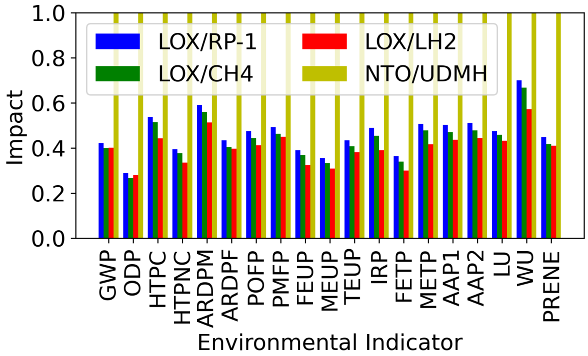

Figure 27: Comparison for 2 stages + booster into LEO

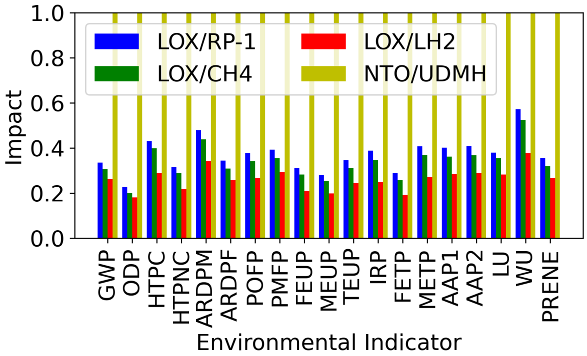

Figure 28: Comparison for 2 stages + booster into GTO

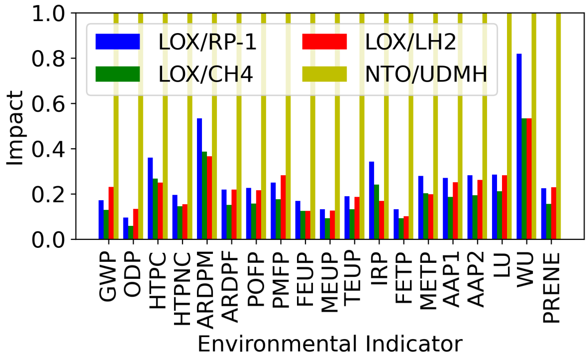

Figure 29: Comparison for 3 stages into LEO

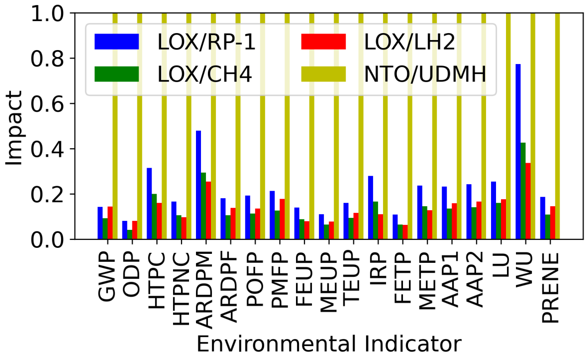

Figure 30: Comparison for 3 stages into GTO

A comparison of the 2-stage systems with booster also shows the greatest influence of NTO/UDMH (Fig. 27 and 28). In second place for LEO follows LOX/RP-1 for all indicators. In third place LOX/CH4 has the highest influence for 17 indicators, LOX/LH2 is in third place for GWP and ODP. For GTO, LOX/RP-1 is also in second place, followed by LOX/CH4 in third place. The comparison of the three-tier systems again shows the greatest influence by the NTO/UDMH system (Fig. 29 and 30). LOX/RP-1 follows in second place for LEO with 15 indicators, and LOX/LH2 is in second place for GWP, ODP, PMFP and PRENE. For GTO, LOX/RP-1 is second for 17 indicators, LOX/LH2 for GWP and ODP.

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4.6 Classification and accuracy of results

In Fig. 31, the influence of the structural factor on the environmental impact becomes visible. The smaller the structural factor, the lower the environmental impact. This shows the great influence that the choice of a correct structural factor has on the results of this study. This must be taken into account when comparing fuel systems with each other. For the present study, fixed structure factors of a respective typical carrier system of the respective architecture were taken. The structure factor is influenced by many parameters, such as material selection, joint, component design, engine cycle, tank insulation, etc. In order to get the most accurate results, therefore real data have to be taken into account, which is only in rare cases publicly available for launcher systems. Further, the analysis shows that lightweight design can reduce the environmental impact for the same choice of material.

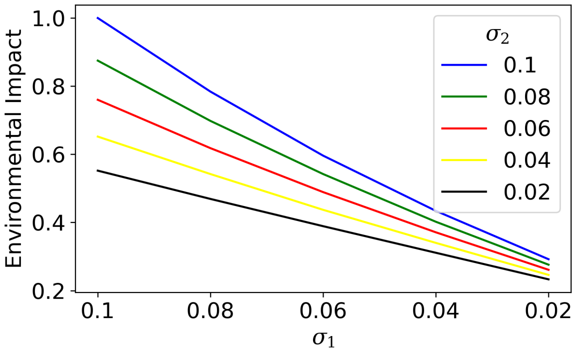

Figure 31: Environmental impact dependent on structural factor

In addition, there is a linear dependence of the underlying environmental factors, which must be questioned by a detailed sensitivity analysis. However, correct structural factors and mass data, other production processes, subsystem mass distribution and energy mixes published by all launcher manufacturers would be needed for better environmental indicators and analyses. The underlying data take into account the current production in Europe and launch preparations in Kourou. Therefore, production in the USA or China is subject to other environmental influences. Therefore, this study can only present an order of magnitude of the environmental impact of the production of the systems studied and by no means a detailed LCA. In order to perform a detailed analysis of a launcher system, the production processes, materials, construction and mass distribution of the systems must be precisely known. However, for a first academic comparison of different launcher architectures and a first estimation of the environmental impact the presented methodology and data are very sufficient.

4.7 Recommendations for more environmentally friendly rockets

Based on the results presented, measures will now be discussed to make the production of launchers more environmentally friendly. First of all, fuel production offers great potential. On the one hand, most fuel production facilities can be converted to sustainable alternatives, such as electrolysis or power-to-gas, and thus offer the potential to enable sustainable fuels using renewable energy. The large share of fuel production in the overall impact and testing of engines could thus be significantly reduced. Here, overlaps with other industries are also advantageous, as hydrogen technology in particular is becoming increasingly important in the aviation and automotive sectors.

Another approach is to improve the manufacturing of the engine, thrust structures and tanks for the stages. The production and processing of metallic materials are energy-intensive processes with a high impact. Here, production should be switched to renewable energies and reuse of the structures should be examined in order to reduce the environmental impact of production per flight. A comparison of the stages shows that two-stage systems have the lowest environmental impact in almost all cases and should therefore be preferred to 3-stage systems and systems with boosters from an environmental point of view. Where possible, solid boosters should be avoided, as their propellants in particular have a significant environmental impact. However, this poses a challenge for pure LOX/LH2 systems, as these are generally not used for their own propulsion due to the high structural mass. The comparison of the propellants shows that the LOX/CH4 and LOX/LH2 systems have the lowest environmental impact for most cases and should therefore be preferred for future launcher systems.

Further, the presented methodology could represent a new approach to be able to calculate the environmental impact during the early phases of launcher development. Based on the calculated data, trade-offs of different launcher architectures with respect to their environmental impact can be performed. For future development, sustainability can therefore be established as a criterion in launcher development in addition to cost, time and performance aspects.

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5. Conclusions

The study shows for the first time a scientific insight into the environmental impact of production of launchers. For this purpose, generic environmental indicators for the production of Ariane 6 version A64 subsystems were developed from ArianeGroup within the framework of an LCA and made available to the University of Stuttgart for evaluation. Using stage optimization and literature values for the system masses, 2- and 3-stage systems as well as 2-stage systems with solid boosters were analyzed with respect to their environmental impact during production. For this purpose, different fuel combinations and target orbits were considered. This methodology of rapidly estimating environmental impact using generic subsystem data during early launcher system design represents a new approach.

Using the example of a two-stage LOX/LH2 launcher with solid boosters, the major influences in production are discussed in detail. It is shown that the engine and the thrust structure and tanks in particular have a high influence on the environmental impact. A comparison of the manufacturing, assembly, testing and transportation phases also shows a high impact of the testing phase, driven by the consumption of propellants during testing of the engine. A comparison with the normalization factors of the PEF shows a high influence of the production of rockets especially for FETP, ARDPF, FEUP, ARDPM as well as AAP1 and GWP.

The comparison of different staging concepts shows that the 2-stage system for LOX/RP-1 and LOX/LH2 launchers has the lowest environmental impact compared to a 3-stage system and 2-stage system with boosters. For LOX/CH4, the impact of 2- and 3- stages is comparable. In comparison of different propellants, NTO/UDMH rockets show a particularly high impact compared to all other propellants. This is due to the propellant production, which has a remarkably high impact. LOX/CH4 and LOX/LH2 have the lowest impact for most environmental indicators and orbits and should be chosen for future development of launchers regarding environmental aspects.

In another comparison, the influence of booster choice on environmental impact was considered. For most environmental indicators, the choice of liquid boosters instead of solid fuels has a positive effect. Especially the propellant production of solid boosters has a major impact. However, more detailed analysis of the structural factor, among other things, must be taken into account in order to be able to make a precise statement.

It was shown in the study that the structural factor has a significant influence on the results. Therefore, this must always be taken into account when considering the results. Without precise structural factors and subsystem masses, this calculation method is therefore only an estimation based on the assumption of production in Europe.

This study is the first to show the overall impact of launch vehicle production on the environment by using 19 environmental indicators to highlight the impact depending on staging concepts, propellant choice, orbit and structural factors. For a comprehensive life cycle assessment covering the complete life of a launcher, more aspects need to be considered. For example, launch emissions and the environmental impact of re-entry have not yet been considered in this study. Further, aspects such as reuse to minimize the production impact raise questions regarding the environmental benefits and are interesting research areas. These points will be the subject of future research.

6. Acknowledgments

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References

[1] McKinsey & Company. The role of space in driving sustainability, security, and development on earth: Five actions that leaders can take to maximize the potential of the sector and its benefits for humanity., 2022.

[2] Johan Rockström, Joyeeta Gupta, Dahe Qin, Steven J. Lade, Jesse F. Abrams, Lauren S. Andersen, David I. Armstrong McKay, Xuemei Bai, Govindasamy Bala, Stuart E. Bunn, Daniel Ciobanu, Fabrice DeClerck, Kristie Ebi, Lauren Gifford, Christopher Gordon, Syezlin Hasan, Norichika Kanie, Timothy M. Lenton, Sina Loriani, Diana M. Liverman, Awaz Mohamed, Nebojsa Nakicenovic, David Obura, Daniel Ospina, Klaudia Prodani, Crelis Rammelt, Boris Sakschewski, Joeri Scholtens, Ben Stewart-Koster, Thejna Tharammal, Detlef van Vuuren, Peter H. Verburg, Ricarda Winkelmann, Caroline Zimm, Elena M. Bennett, Stefan Bringezu, Wendy Broadgate, Pamela A. Green, Lei Huang, Lisa Jacobson, Christopher Ndehedehe, Simona Pedde, Juan Rocha, Marten Scheffer, Lena Schulte-Uebbing, Wim de Vries, Cunde Xiao, Chi Xu, Xinwu Xu, Noelia Zafra-Calvo, and Xin Zhang. Safe and just earth system boundaries. *Nature*, 2023.

[3] European Comission. Com(2019) 640 final: The european green deal.

DOI: 10.13009/EUCASS2023-274

[4] Jan-Steffen Fischer and Stefanos Fasoulas. Review of the environmental impact of space transportation systems towards a full life cycle assessment: Iac-22-d2.ip.10.x68113. In *73rd International Astronautical Congress (IAC), Paris, France, 18-22 September 2022.*

[5] Aurélie Gallice, Thibaut Maury, and Encarna del Olmo. Environmental impact of the exploitation of the ariane 6 launcher system. In *Clean Space Industrial Days, Noordwijk, Netherlands, 2018.*

[6] ISO - International Organization for Standardization. Iso 14040: Environmental management – life cycle assessment – principles and framework, 2021.

[7] ISO - International Organization for Standardization. Iso 14044: Environmental management – life cycle assessment – requirements and guidelines, 2021.

[8] Vera Pinto. Eu environmental policies. In *Clean Space Industrial Days, Noordwijk, Netherlands, 2022.*

[9] Julian Austin and Jakob Huesing. Developing a standardised methodology for spacespecific life cycle assessment. In *5th CEAS Air & Space Conference, Delft, Netherlands, 2015.*

[10] Augustin Chanoine. Environmental impacts of launchers and space missions. In *Clean Space Industrial Days 2017, Noordwijk, Netherlands, 2017.*

[11] Sahba El-Shawa, Luisa Innocenti, and Benedetta Margrethe Cattani. From cradle to grave: Esa clean space's approach to space sustainability. In *72nd International Astronautical Congress, Dubai, United Arab Emirates, 2021.*

[12] Thibaut Maury, Philippe Loubet, Sara Morales Serrano, Aurélie Gallice, and Guido Sonnemann. Application of environmental life cycle assessment (lca) within the space sector: A state of the art. *Acta Astronautica*, 170:122–135, 2020.

[13] ESA LCA Working Group. Space system life cycle assessment (lca) guidelines.

[14] Shelia S. Neumann. Environmental life cycle assessment of commercial space transportation activities.

[15] Loïs Miraux, Léonard Pineau, and Pascal Noir. Parametric life cycle assessment of a space launch service based on a lox/biomethane semi-reusable launcher: Iac-22,d2,2,10,x70201. In *73rd International Astronautical Congress (IAC), Paris, France, 2022.*

[16] Guillermo J. Dominguez Calabuig, Loïs Miraux, Andrew Ross Wilson, Alberto Sarritzu, and Angelo Pasini. Eco-design of future reusable launchers: insight into their life cycle and atmospheric impact. In *9TH European Conference for Aeronautcs (EUCASS), Lille, France, 2022.*

[17] Ernst Messerschmid and Stefanos Fasoulas. *Raumfahrtsysteme: Eine Einführung mit Übungen und Lösungen*. Springer Vieweg, Berlin, 5., aktualisierte und ergänzte auflage edition, 2017.

[18] Tory Bruno. Ula launch vehicle wight and bost by major elements. In *Twitter, 01.02.2015.*

[19] Arianespace. Ariane 6 user's manual issue 2 revision 0, 2021.

[20] European Comission. Com(2021)9332 final: Commission recommendation on the use of the environmental footprint methods to measure and communicate the life cycle environmental performance of products.

[21] IPCC. Climate change 2013: The physical science basis. contribution of working group i to the fifth assessment report of the intergovernmental panel on climate change.

[22] World Meteorological Organization. Scientific assessment of ozone depletion: 2014.

[23] Peter Fantke, Marian Bijster, Michael Zwicky Hauschild, Mark Huijbregts, Olivier Jolliet, Anna Kounina, Violaine Magaud, Manuele Margni, Tom E. McKone, Ralph K. Rosenbaum, Dik van de Meent, and Rosalie van Zelm. Usetox 2.0 documentation (version 1.00).

[24] Lauran van Oers, Jeroen B. Guinée, and Reinout Heijungs. Abiotic resource depletion potentials (adps) for elements revisited—updating ultimate reserve estimates and introducing time series for production data. *The International Journal of Life Cycle Assessment*, 25(2):294–308, 2020.

DOI: 10.13009/EUCASS2023-274

[25] Rosalie van Zelm, Mark A.J. Huijbregts, Henri A. den Hollander, Hans A. van Jaarsveld, Ferd J. Sauter, Jaap Struijs, Harm J. van Wijnen, and Dik van de Meent. European characterization factors for human health damage of pm10 and ozone in life cycle impact assessment. *Atmospheric Environment*, 42(3):441–453, 2008.

[26] Peter Fantke, Olivier Jolliet, John Evans, Joshua Apte, Aaron Cohen, Otto HÃ¤nninen, Fintan Hurley, Matti Jantunen, Michael Jerrett, Jonathan Levy, Miranda Loh, Julian Marshall, Brian Miller, Philipp Preiss, Joseph Spadaro, Marko Tainio, Jouni Tuomisto, Charles Weschler, and Thomas McKone. Health effects of fine particulate matter in life cycle impact assessment: Findings from the basel guidance workshop. *The International Journal of Life Cycle Assessment*, 20, 02 2015.

[27] Jaap Struijs, A. Beusen, Dick Zwart, and Mark Huijbregts. Characterization factors for inland water eutrophication at the damage level in life cycle impact assessment. *The International Journal of Life Cycle Assessment*, 16:59–64, 01 2010.

[28] Jyri Seppälä, Maximilian Posch, Matti Johansson, and Jean-Paul Hettelingh. Country-dependent characterisation factors for acidification and terrestrial eutrophication based on accumulated exceedance as an impact category indicator (14 pp). *The International Journal of Life Cycle Assessment*, 11(6):403–416, 2006.

[29] R. Frischknecht, A. Braunschweig, P. Hofstetter, and P. Suter. Human health damages due to ionising radiation in life cycle impact assessment. *Environmental Impact Assessment Review*, 20(2):159–189, 2000.

[30] Jeroen B. Guinee. Handbook on life cycle assessment operational guide to the iso standards. *The International Journal of Life Cycle Assessment*, 7(5), 2002.

[31] Valeria De Laurentiis, Michela Secchi, Ulrike Bos, Rafael Horn, Alexis Laurent, and Serenella Sala. Soil quality index: Exploring options for a comprehensive assessment of land use impacts in lca. *Journal of Cleaner Production*, 215:63–74, 2019.

[32] Anne-Marie Boulay, Jane Bare, Lorenzo Benini, Markus Berger, Michael J. Lathuillière, Alessandro Manzardo, Manuele Margni, Masaharu Motoshita, Montserrat Núñez, Amandine Valerie Pastor, Bradley Ridoutt, Taikan Oki, Sebastien Worbe, and Stephan Pfister. The wulca consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (aware). *The International Journal of Life Cycle Assessment*, 23(2):368–378, 2018.

[33] Volkswagen AG. How the id.3 lowers the carbon footprint, 2021.