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Institute of Space Systems

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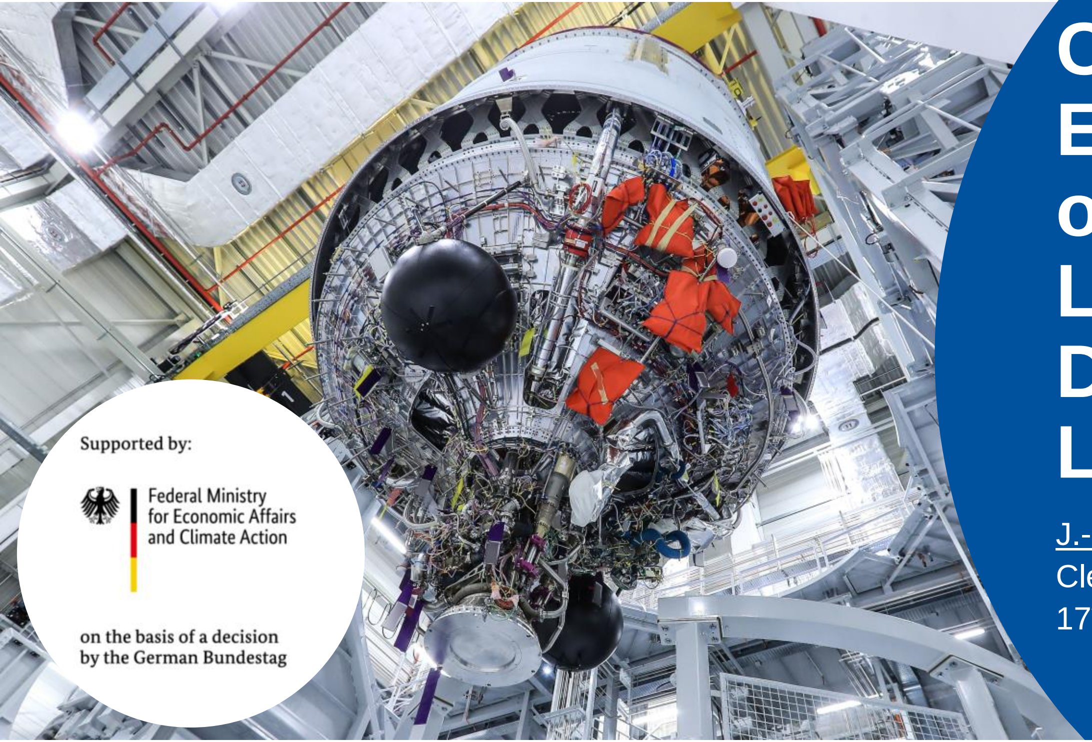

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Federal Ministry
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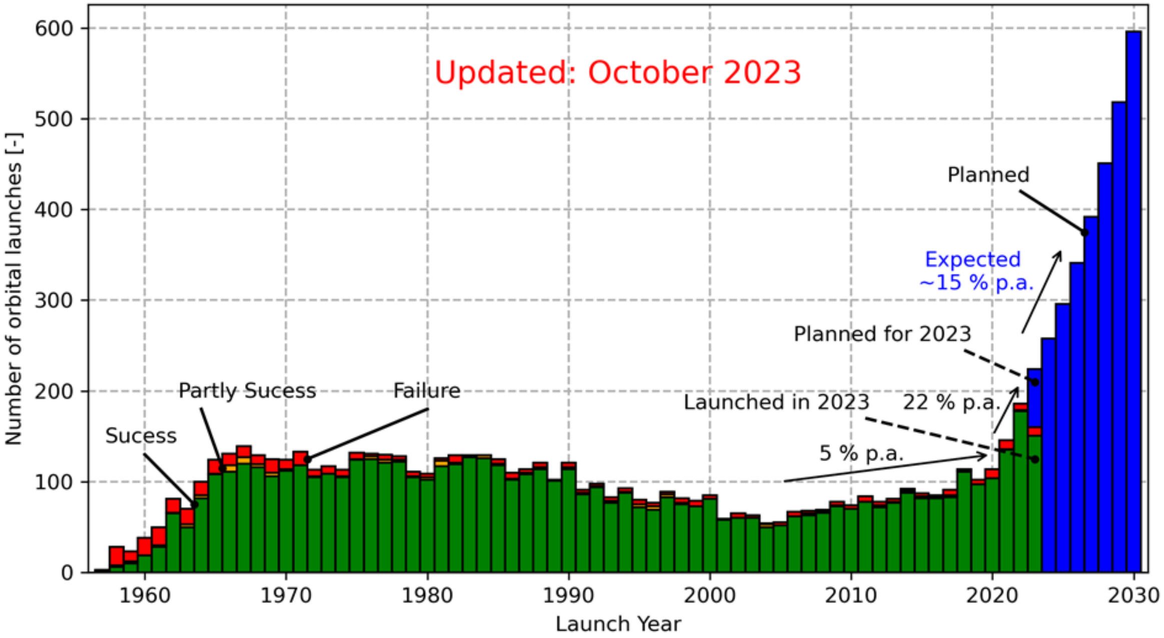
by the German Bundestag

Comparison of the Environmental Impact of Production and Launch Emissions of Different Common Launcher Architectures

J.-S. Fischer, S. Fasoulas, C. Brun-Buisson, Dr. E. del Olmo
Clean Space Industry Days 2023, Noordwijk
17th October 2023

Motivation

How can we make space flight sustainable?



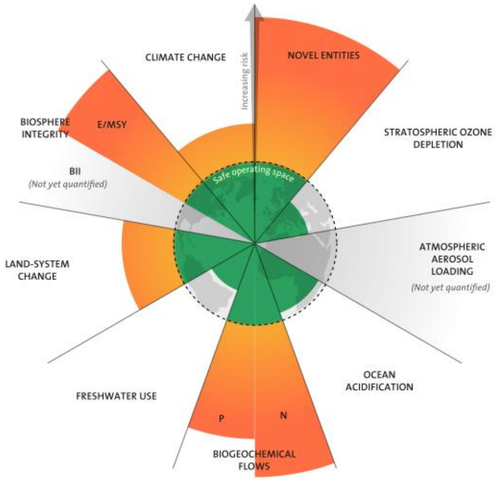


Fig. 2: Planetary boundaries [1]

Fig. 1: Historical and expected future space launches into orbit

Life Cycle Assessment of Space Transportation Systems @ Uni Stuttgart

Project and study goals

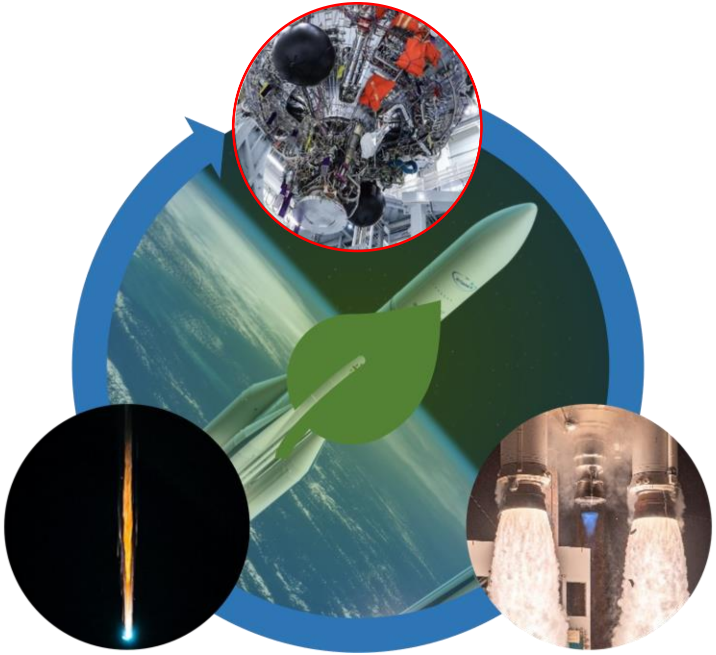


Fig. 3: Life cycle phases of rockets

- Assessment of the environmental impact of space transportation systems considering all life cycle phases
- Cooperation with ArianeGroup to develop a generic dataset regarding production
    - Identification of Hot-Spots
    - Comparison of different launch system architectures
    - Comparison of different propellant systems
    - Impact of reusability
- Today: presentation of study results

Methodology

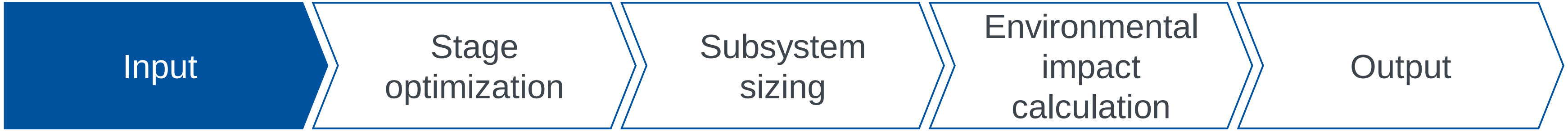
Assumptions used for the study

Tab. 1: Considered orbits and required velocity

Orbits	Δv [km/s]
LEO (e.g. EO, Constellation)	9.0
MEO (e.g. Navigation)	10.0
GTO (e.g. Communication)	11.6
Trans Lunar Orbit Insertion (e.g. Exploration)	12.0
Trans Mars Orbit Insertion (e.g. Exploration)	15.0

Tab. 2: Considered propellants and their effective velocity

Propellant combination	Effective velocity	
	Sea level	Vacuum
LOX/LH2	3050	4400
LOX/CH4	3200	3550
LOX/RP-1	3050	3425
UDMH/NTO	2500	2950
Solid (APN/Al/HTPB)	2750	2900



Methodology

Stages* launched in 2022

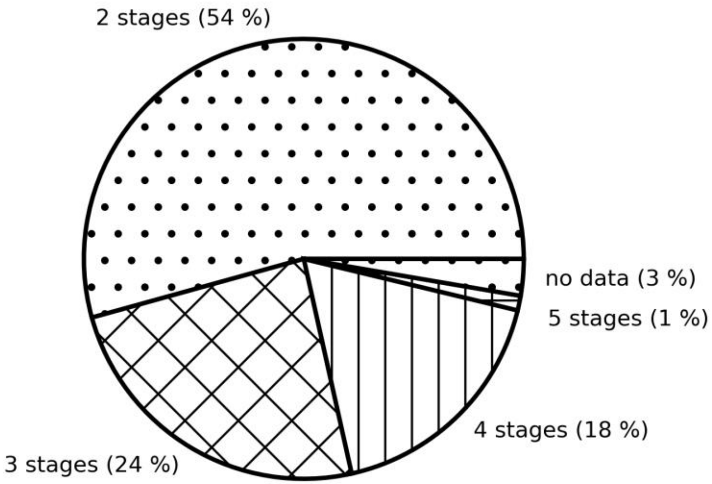


Fig. 4: Stages launched in 2022

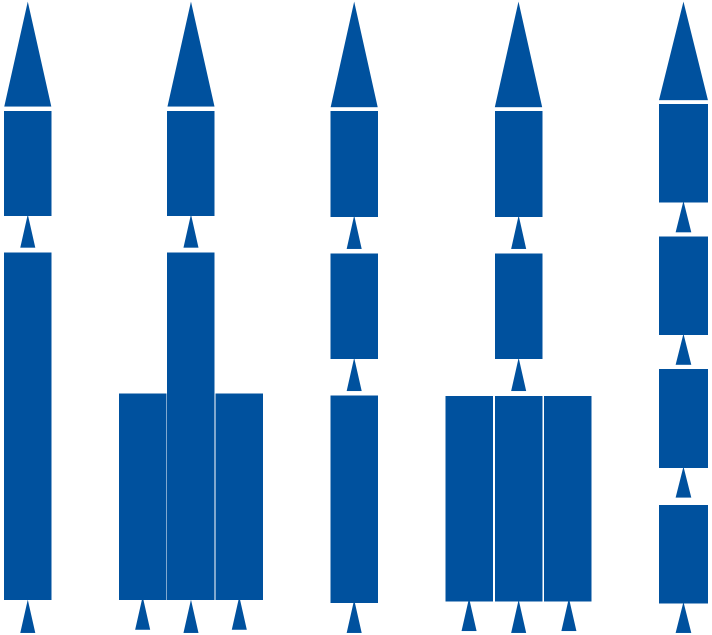


Fig. 5: Different tandem and parallel staging concepts

Input → Stage optimization → Subsystem sizing → Environmental impact calculation → Output

*stage = booster/core stage/upper stage of a launch vehicle

Methodology

Stage optimization towards maximum payload

- General:

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

- 2-stage system:

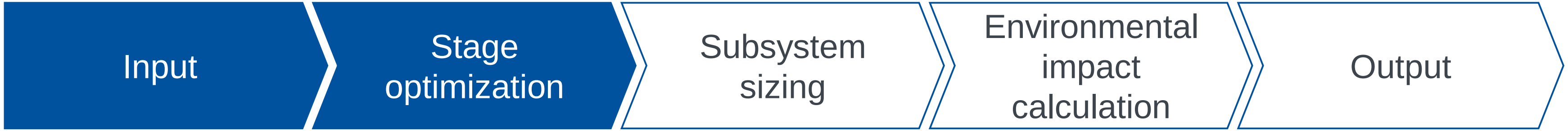
$$\mu_l = \left(\frac{\mu_1}{\mu_1\sigma_1 + \mu_2}\right)^{\frac{c_{e,1}}{c_{e,2}}} e^{\frac{-\Delta V}{c_{e,2}}} \mu_2 - \mu_2\sigma_2$$

- 3-stage system:

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

  - Optimization:

$$\frac{\delta\mu_l}{\delta\mu_2} = f(\mu_2, \ldots) = 0 \qquad \frac{\delta\mu_l}{\delta\mu_2\delta\mu_3} = f(\mu_2, \mu_3, \ldots) = 0$$



Methodology

Staging concepts in this study

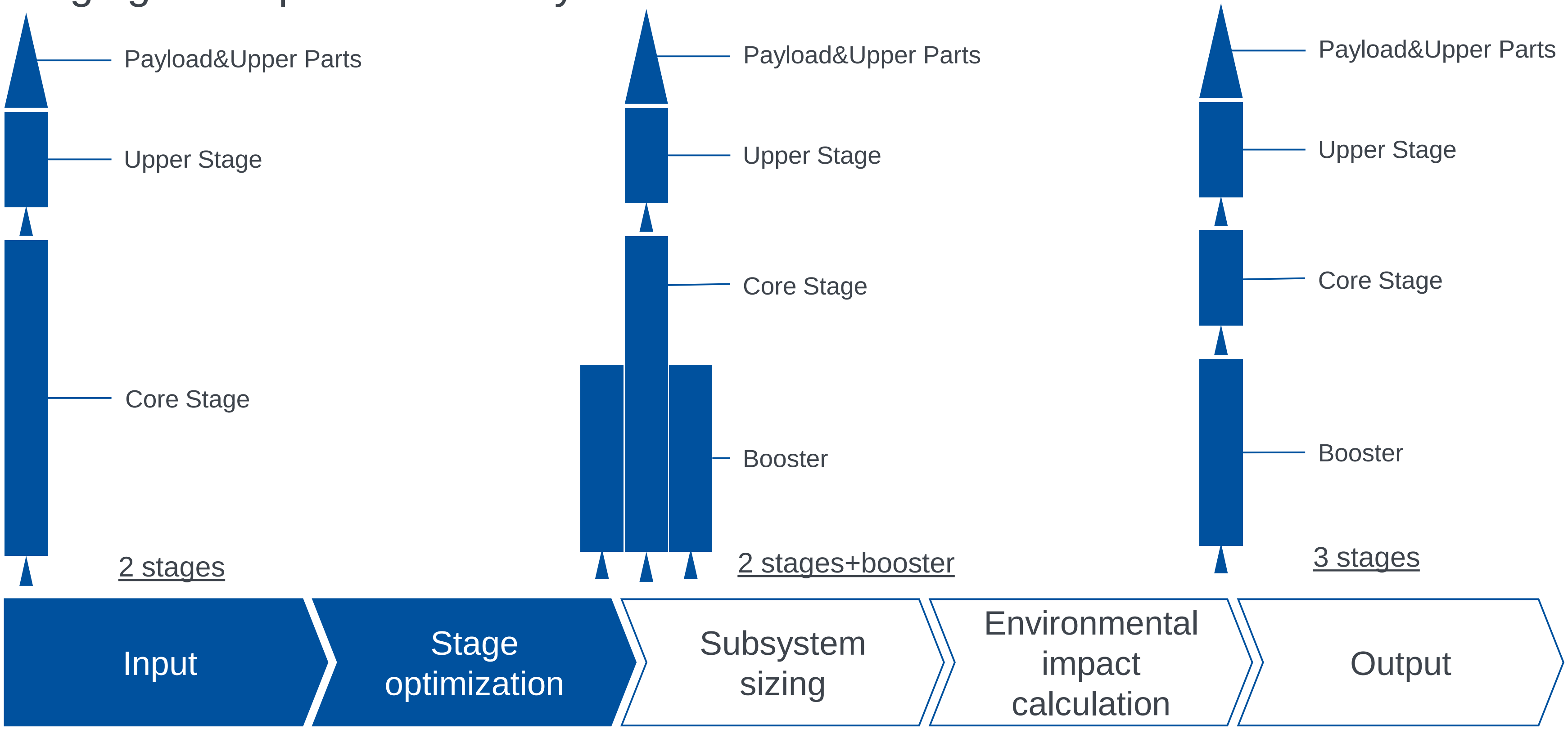


Fig. 6: Staging concepts considered in this study

Methodology

Subsystem mass estimation

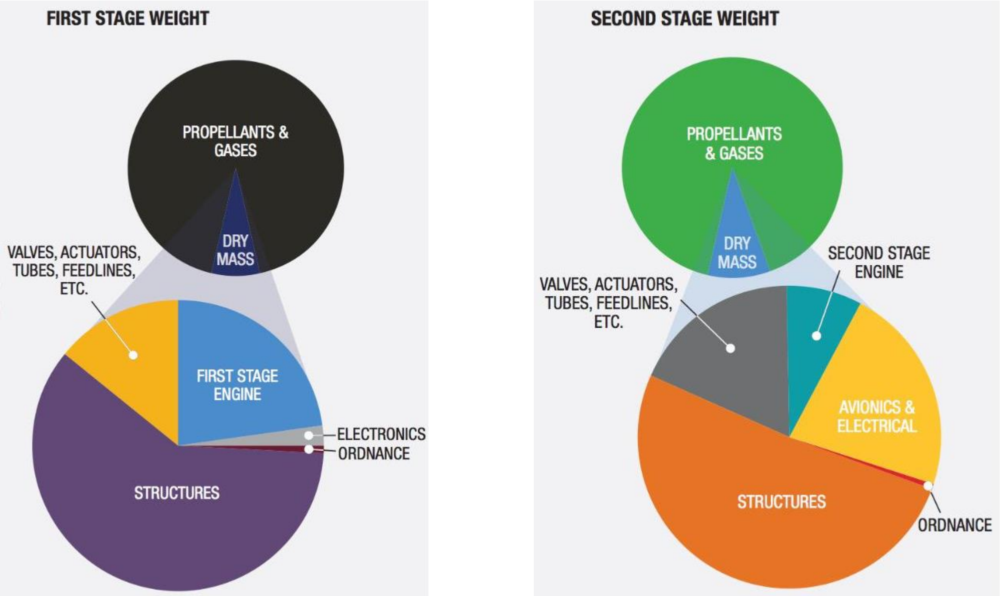


Fig. 7: Subsystem weight distribution for core and upper stage [3]

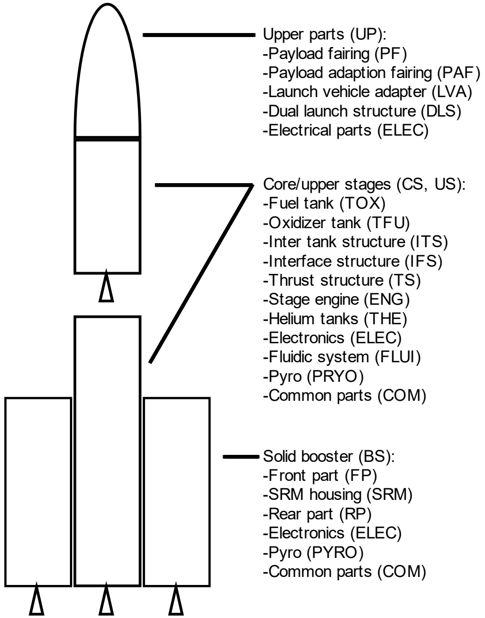
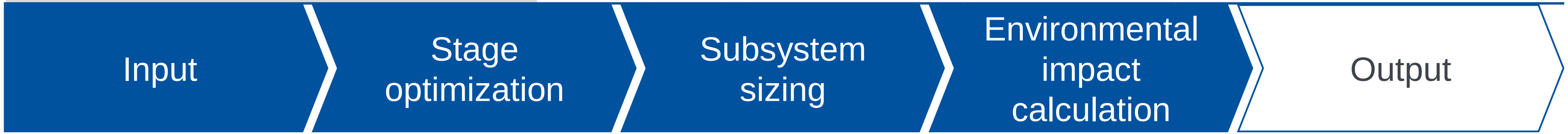


Fig. 8: Subsystems data provided by ArianeGroup

Input → Stage optimization → Subsystem sizing → Environmental impact calculation → Output

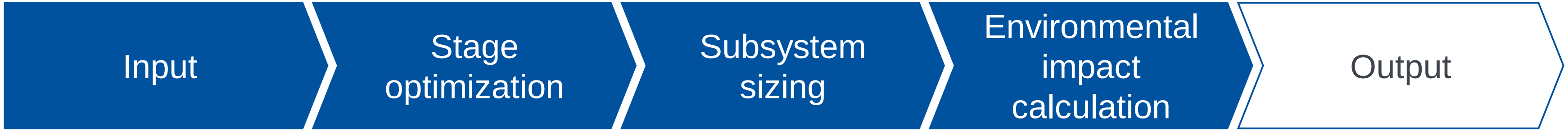
Methodology

Environmental indicator	ESA	PEF	Abbreviation	Unit	Calculation Method
Global warming potential (100 y)	X	X	GWP	kg CO2 eq.	IPCC2013
Ozone depletion potential	X	X	ODP	kg CFC-11 eq.	WMO 2014 + integrations
Human toxicity potential, cancer	X	X	HTPC	CTUh	USEtox model 2.1
Human toxicity potential, non-cancer	X	X	HTPNC	CTUh	USEtox model 2.1
Abiotic resource depletion potential (metal and mineral resources)		X	ARDPM	kg Sb eq.	CML 2002 (ultimate reserve)
Abiotic resource depletion potential (fossil fuels)	X	X	ARDPF	MJ	CML 2002
Photochemical ozone formation potential	X	X	POFP	kg NMVOC eq.	ReCiPe 2008
Particulate matter formation potential	X	X	PMF	Disease incidence	PM UNEP 2016
Freshwater eutrophication potential	X	X	FEUP	kg P eq.	ReCiPe 2008



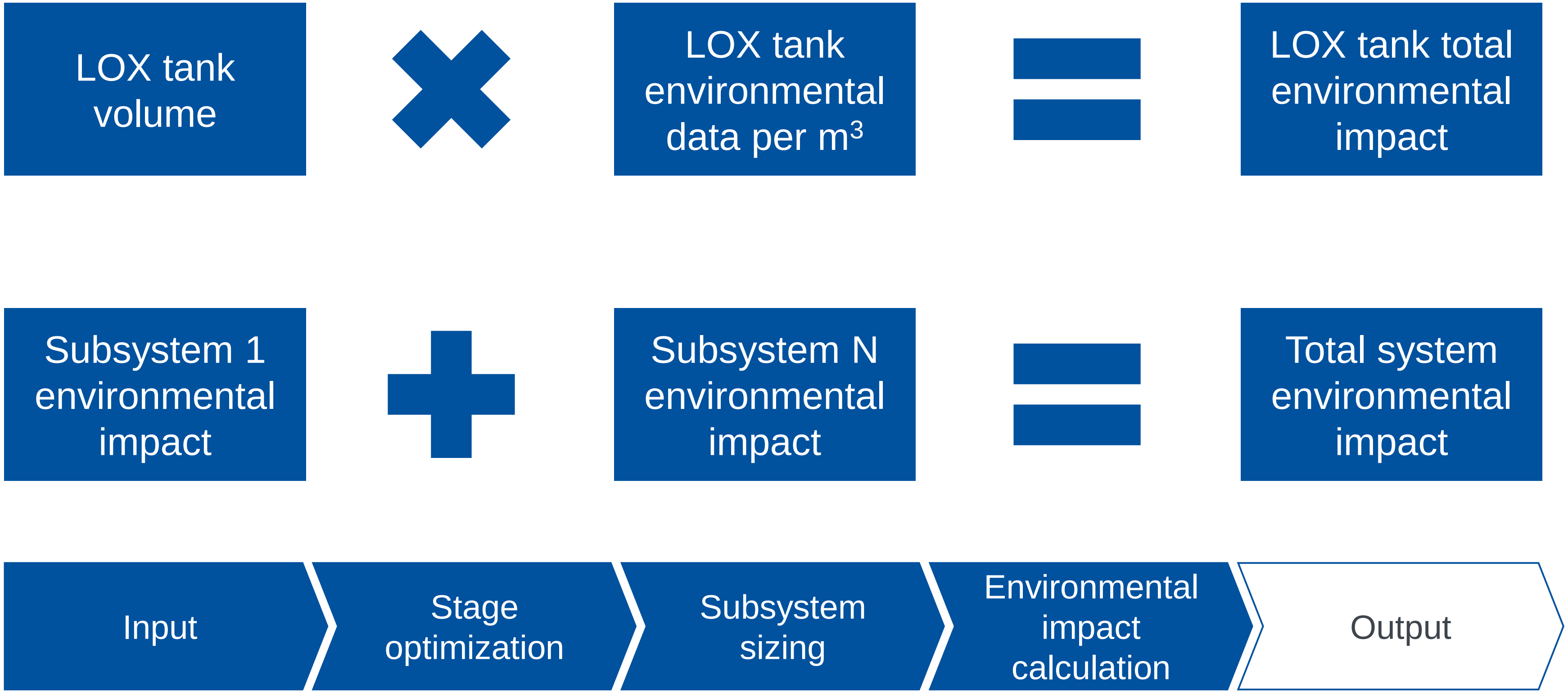
Methodology

Environmental indicator	ESA	PEF	Abbreviation	Unit	Calculation Method
Marine eutrophication potential	X	X	MEUP	kg N eq.	ReCiPe 2008
Terrestrial eutrophication potential		X	TEUP	mol N eq.	Accumulated exceedance
Ionising radiation potential	X	X	IRP	kBq U 235 eq.	Frischknecht et al., 2000
Freshwater ecotoxicity potential	X	X	FETP	CTUe	USEtox model 2.1
Marine ecotoxicity potential	X		METP	kg 1,4-DB eq.	CML 2002
Air acidification potential (PEF)		X	AAP1	mol H+ eq.	Accumulated exceedance
Air acidification potential (ESA)	X		AAP2	kg SO2 eq.	CML 2002
Land use		X	LU	Dimensionless (pt)	LANCA
Water use		X	WU	m3 world eq.	AWARE
Primary Energy Consumption Potential	X		PRENE	MJ	ESA LCA 2020



Methodology

Impact calculation example tank



Methodology

Impact calculation launch emissions

Tab. 3: Launch emission calculation (kg per kg burned propellant)

	LOX/RP-1	LOX/CH4	LOX/LH2	UDMH/NTO	Solid (HTPB1912)
CO_2	3.15	2.74	0	1.46	0.39
H_2O	1.26	2.25	8.94	1.2	0.28
N_2	0	0	0	1.4	0.08
HCl	0	0	0	0	0.21
Al_2O_3	0	0	0	0	0.36

- CO_2 emissions as 1:1 CO_2-eq.
- Effects of other emissions (H_2O, NO_x, soot) are not taken into account, these can have potentially an very high influence on radiative forcing and ozone depletion
- for high-atmosphere emissions, there are no verified GWP100 values (see also “Further development of LCA methodology for reusable and sustainable launchers”, in Ascension Conference, 2023)

Input → Stage optimization → Subsystem sizing → Environmental impact calculation → Output

Methodology

Results for 2 stages (LOX/LH2)+booster for 25 t into LEO

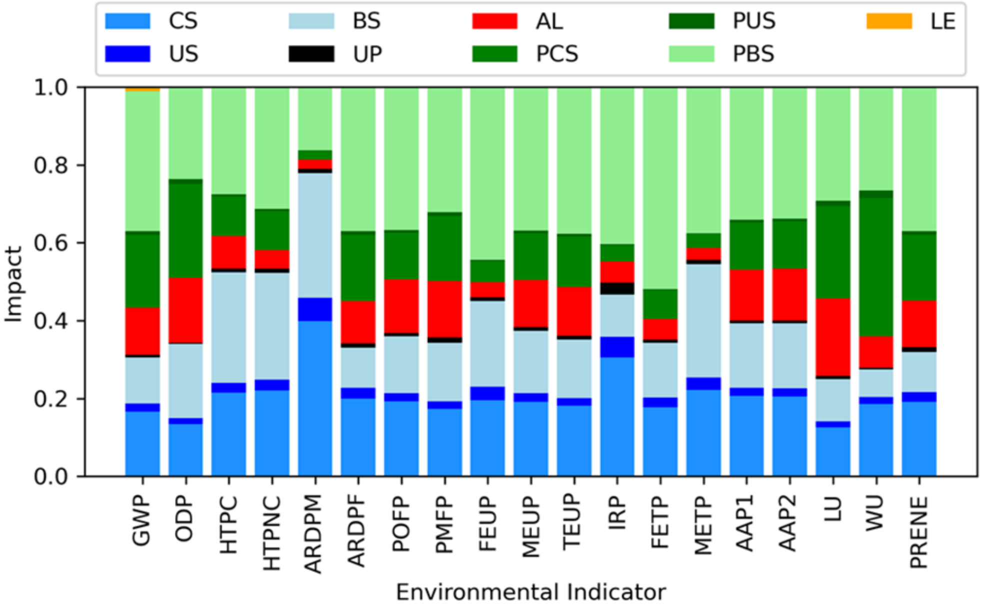


Fig. 9: Share of systems to total environmental impact

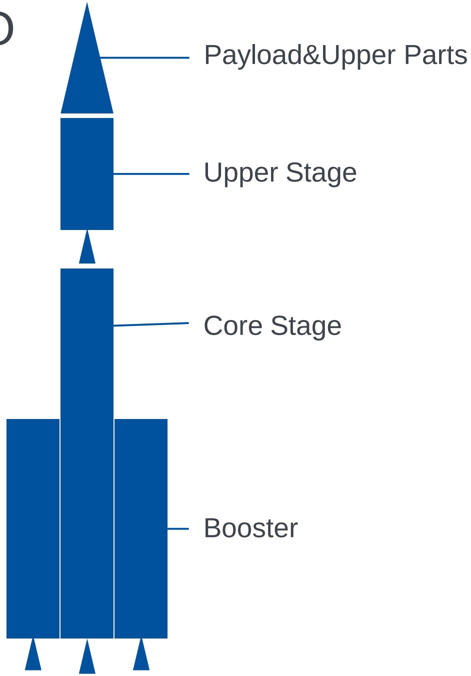
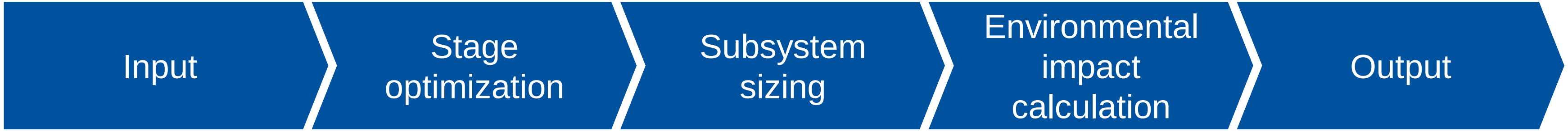


Fig. 10: Considered 2 stages + booster concept



Results

Environmental impacts of core stage subsystems

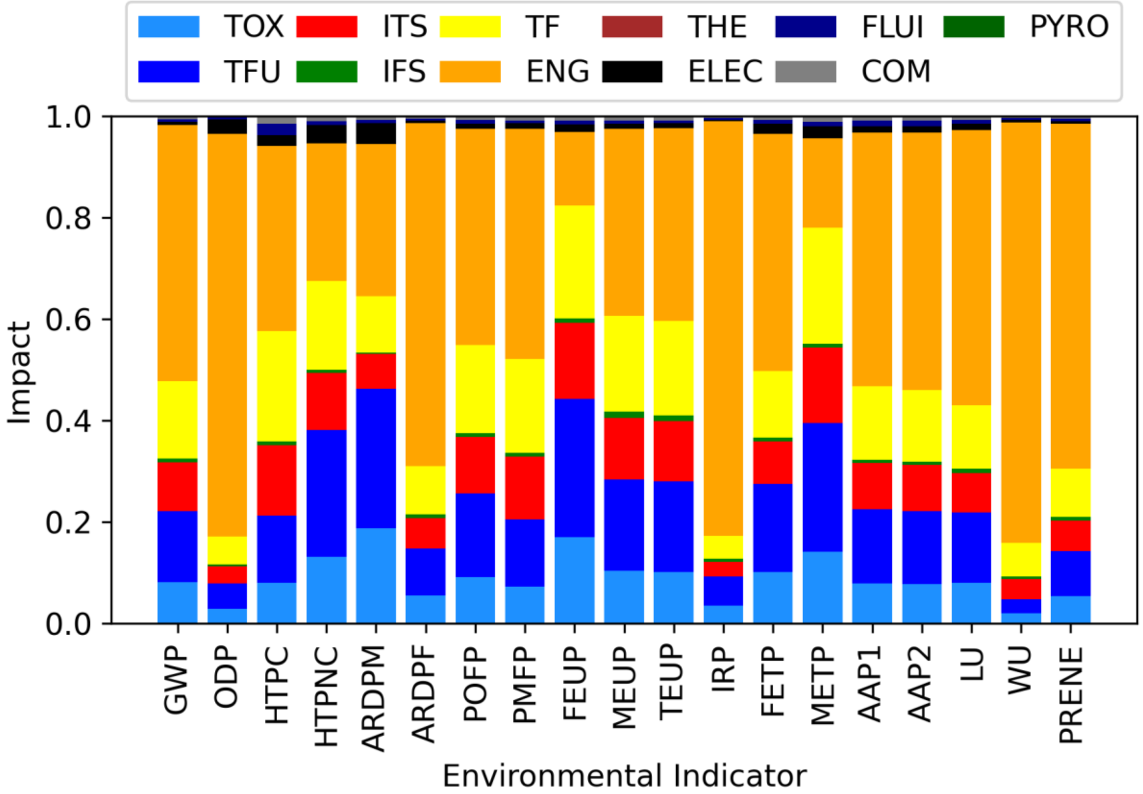


Fig. 11: Environmental indicators for core stage subsystems

- Very high impact from engine (>50% for GWP, ODP, ARDPF, IRP, AAP1, AAP2, LU, WU and PRENE)
- High impact from thrust structure, inter-tank structure, fuel tank and oxidizer tank
- Fuel tank has 1.7 times the impact of the oxidizer tank, although it has 2.8 times the volume

Results

Environmental impacts of booster stage subsystems

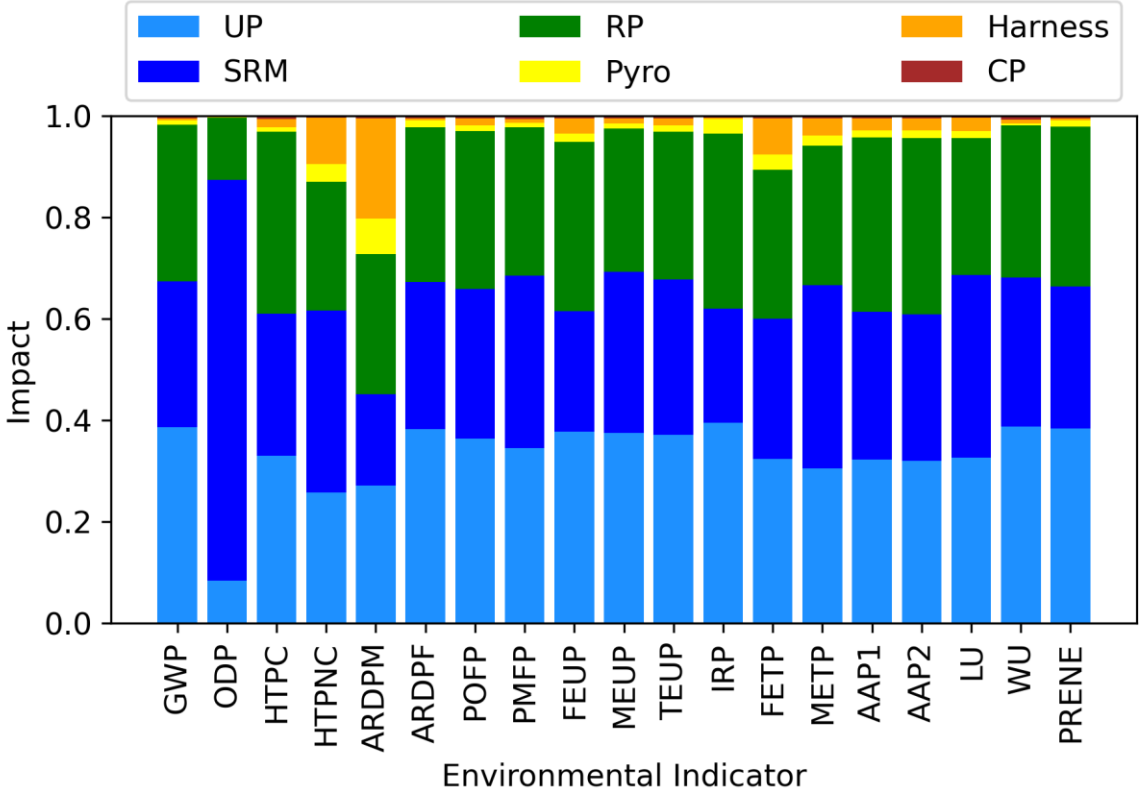


Fig. 12: Environmental indicators for booster stage subsystems

- Upper part and SRM housing have the highest impact
- High ODP impact due to carbon fiber
- Harness influences ARDPM and HTPNC

Results

Environmental impacts of upper parts subsystems

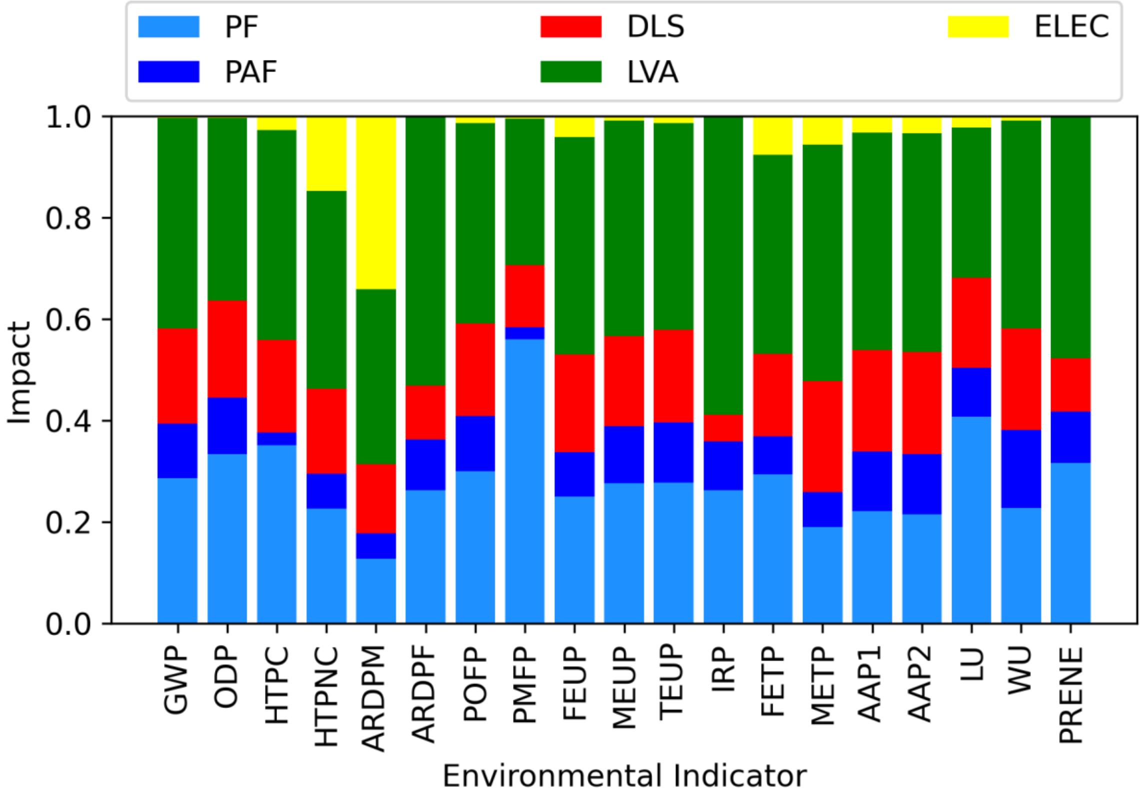


Fig. 13: Environmental indicators for upper parts subsystems

- LVA and payload fairing have the highest impact
- DLS and PAF following
- Electronics only for ARDPM and HTPNC

Results

Environmental impacts of core stage production steps

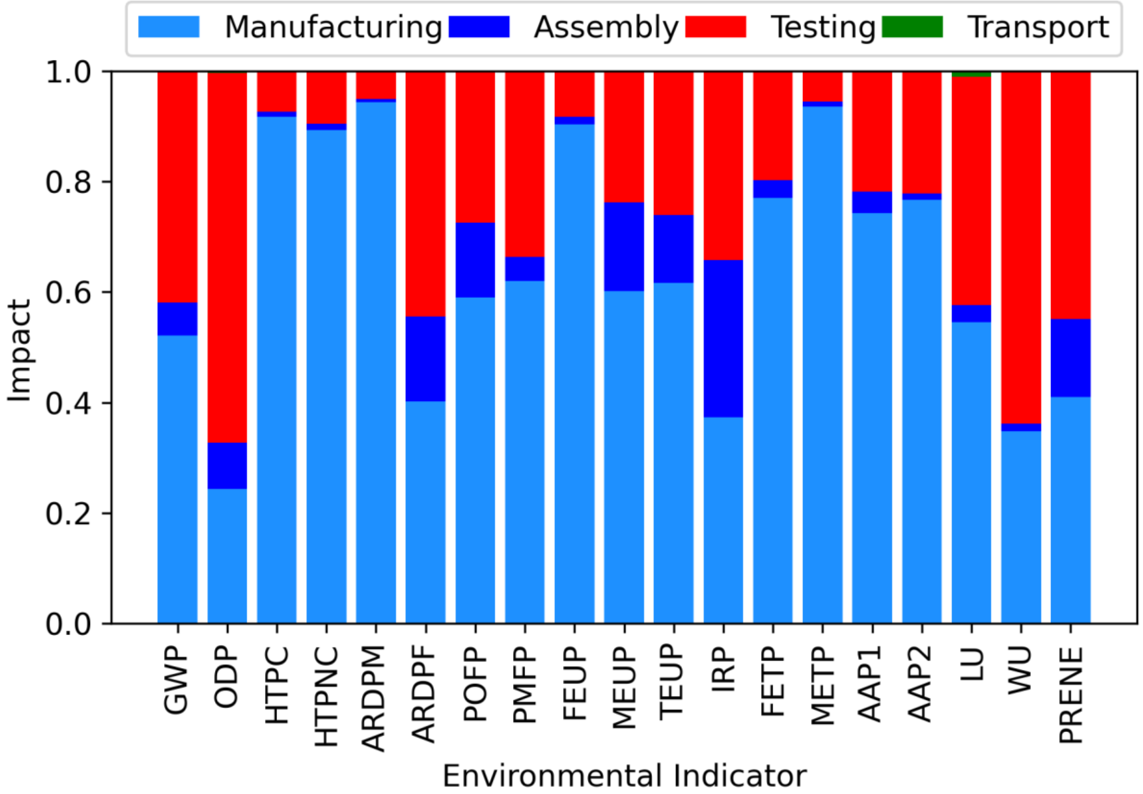


Fig. 14: Environmental indicators for core stage production

- High impact from manufacturing, 64% on average
- Testing 29% on average, driven by engine tests, >50% on ODP and WU
- Assembly 10% on ARDPF, POFP, MEUP, TEUP, IRP and PRENE

Results

Environmental impacts of dry mass production steps

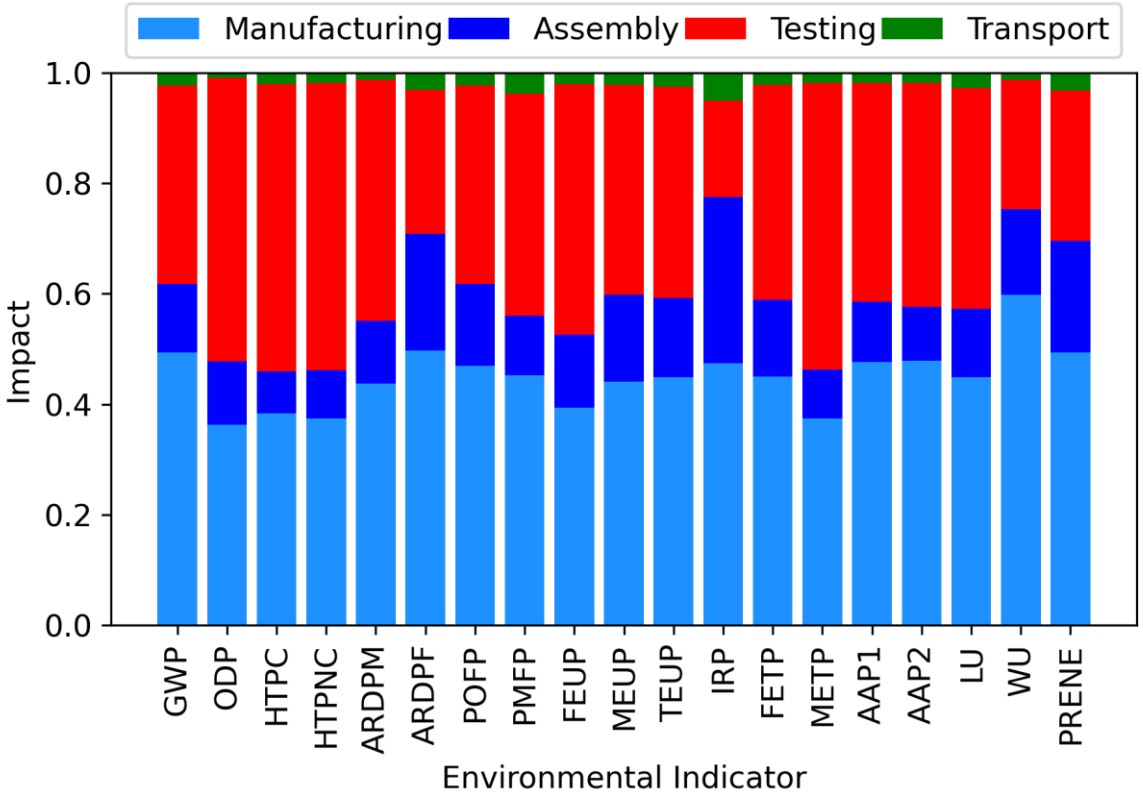


Fig. 15: Environmental indicators for dry mass production

- Manufacturing is on average at 45%
- Testing: 39%
- Assembly: 14 %

Results

Environmental impacts of propellant production steps

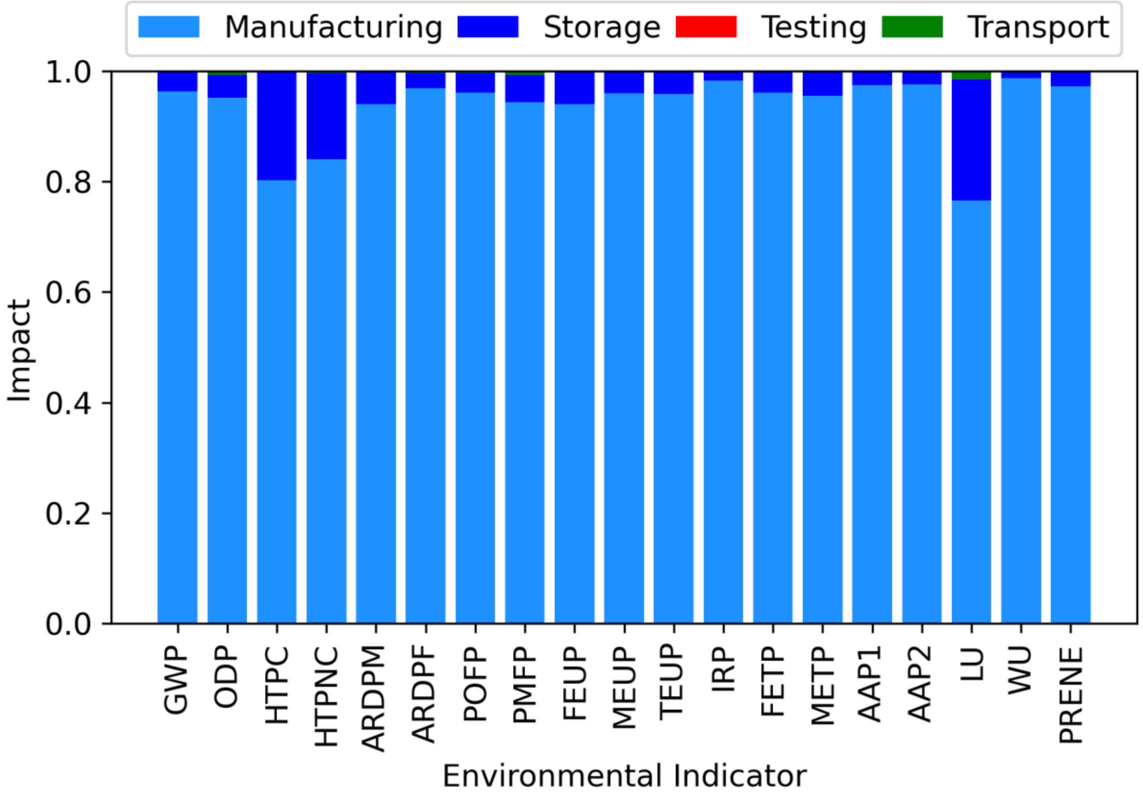
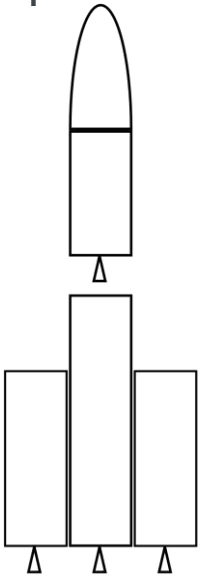


Fig.16: Environmental indicators for propellant production

- Manufacturing has the highest impact
- Storage has an impact >15% for HTPC, HTPNC and LU

Results

Comparison with automotive industry (LOX/LH2 Launcher 25t LEO)



=

x 1

x 1290

17675 t CO2-eq.

13.7 t CO2-eq. per middle-class BEV [4]

Fig. 17: Comparison of GWP100 of a launcher to automotive production (only to illustrate the order of magnitude!)

Results

Comparison of different booster concepts

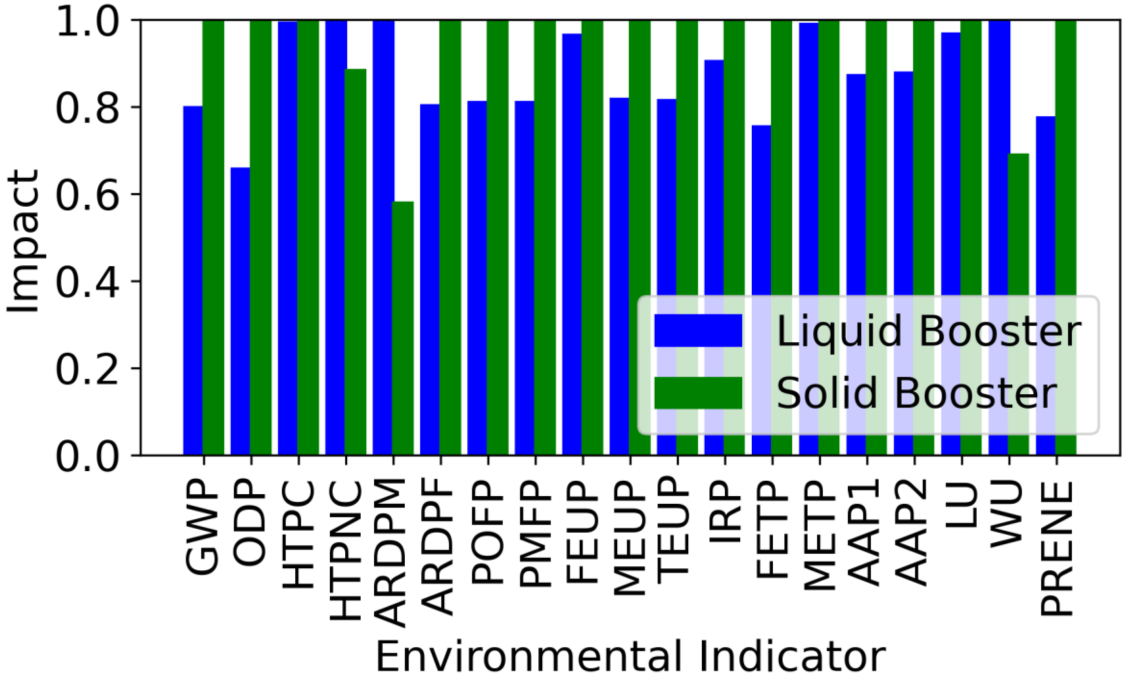


Fig. 18: Normalized environmental indicators for launcher production

- LOX/LH2 system with solid vs. liquid CH4 booster
- Reduction to 87% in average
- Higher Impact for WU, ARDPM and HTPNC

Results

Comparison of different staging concepts

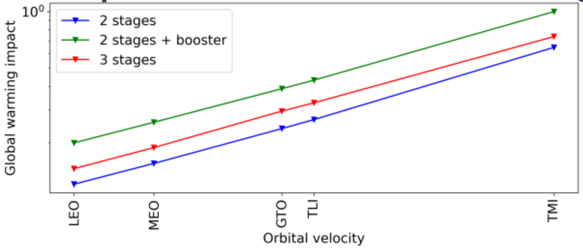


Fig. 19: Comparison of GWP for LH2

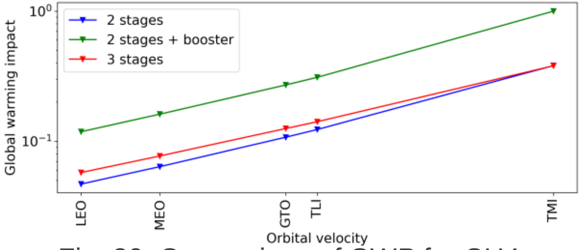


Fig. 20: Comparison of GWP for CH4

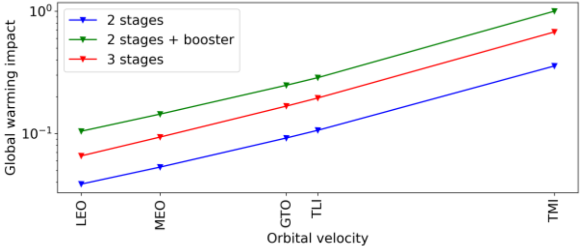


Fig. 21: Comparison of GWP for RP-1

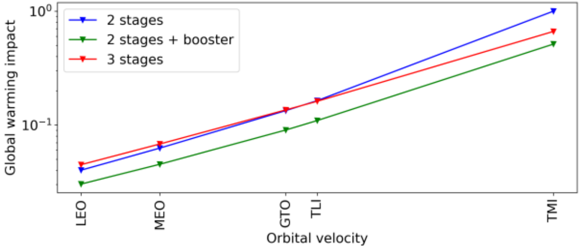


Fig. 22: Comparison of GWP for UDMH

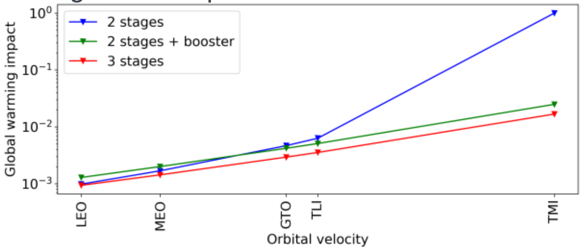


Fig. 23: Comparison of GWP for solid

- Most concepts (3/5) have a lower impact without boosters
- 2 stages in 3/5 cases better than 3 stages
- Different results for UDMH due to high propellant production impact
- 2-stage solid very high for TMI due to inefficient staging (high structural mass)

Results

Comparison of different propellants

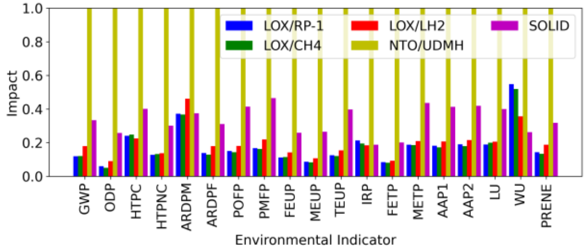


Fig. 24: Comparison for 2 stages (LEO)

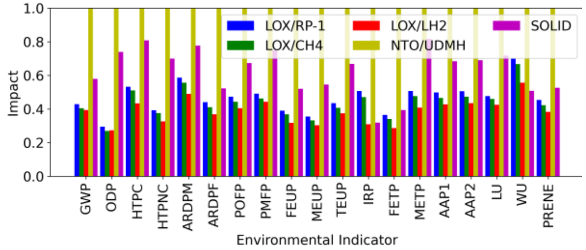


Fig. 25: Comparison for 2 stages+booster (LEO)

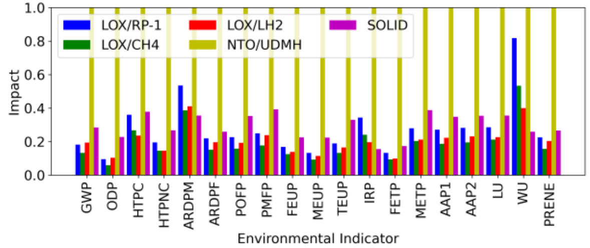


Fig. 26: Comparison for 3 stages (LEO)

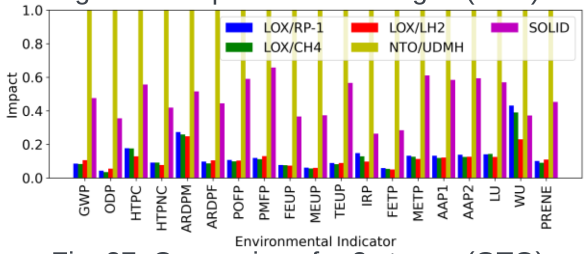


Fig. 27: Comparison for 2 stages (GTO)

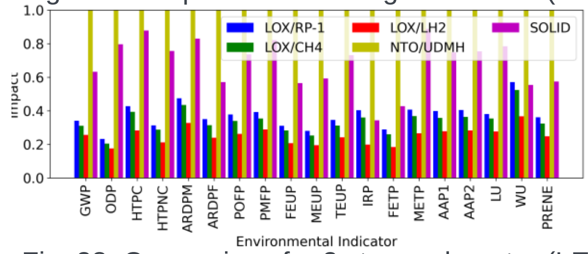


Fig. 28: Comparison for 2 stages+booster (LEO)

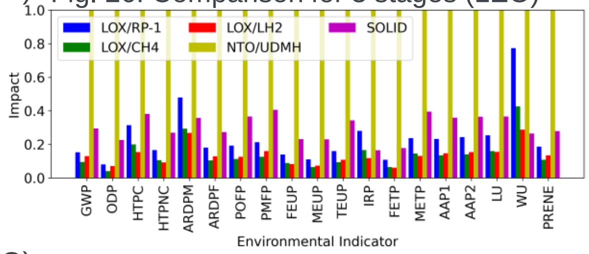


Fig. 29: Comparison for 3 stages (GTO)

- UDMH has the highest impact for all systems and indicators → high impact of fuel production
- Second highest impact solid fuel systems for most environmental indicators
- Third highest impact in most cases LOX/RP-1 (2 stages to GEO, 2 stages + booster, 3 stages)

→ LOX/CH4 and LOX/LH2 the "greenest" choice in terms of production (conventional)

Results

Impact of reuse for 2-stage LOX/RP-1 systems (per t in LEO)

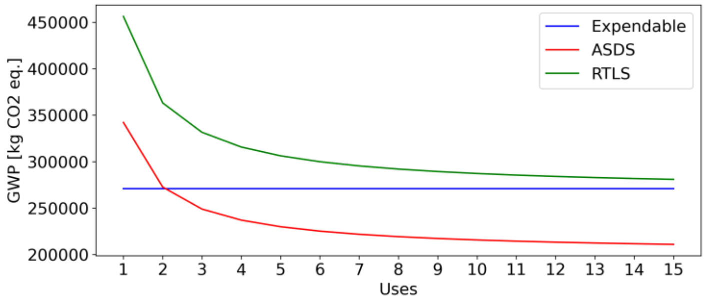


Fig. 30: Comparison of GWP for reuse

- For ASDS, 17/19 of the indicators improve
- For RTLS, 15/19 of the indicators improve
- Higher impact for land and water use
- Reduction of >50% for ASDS and >30% for RTLS for ARDPM, IRP and METP

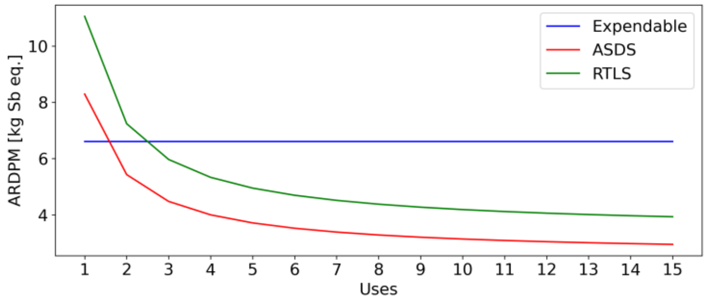


Fig. 31: Comparison of the ARDPM for reuse

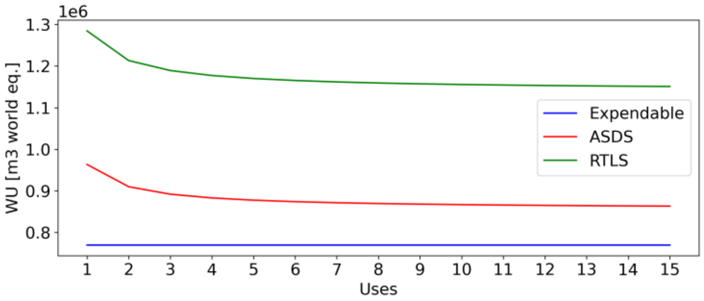


Fig. 32: Comparison of the WU in case of reuse

Results

Impact of reuse for 2-stage LOX/RP-1 systems (per t in LEO)

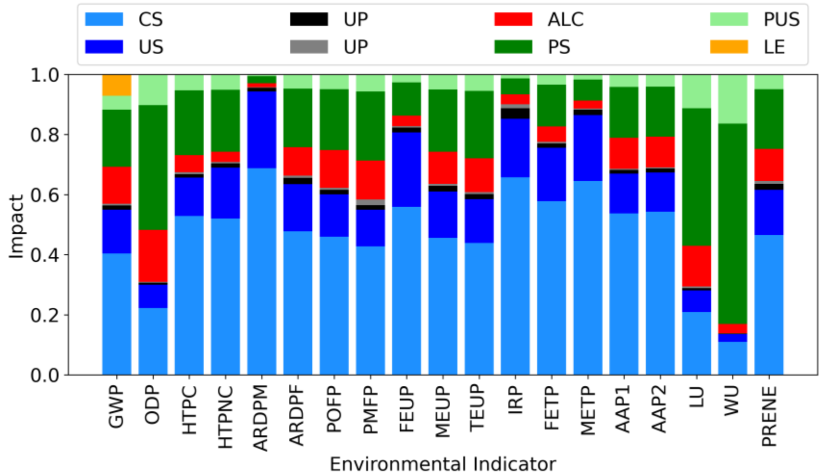


Fig. 34: Share of environmental indicators for conventional systems

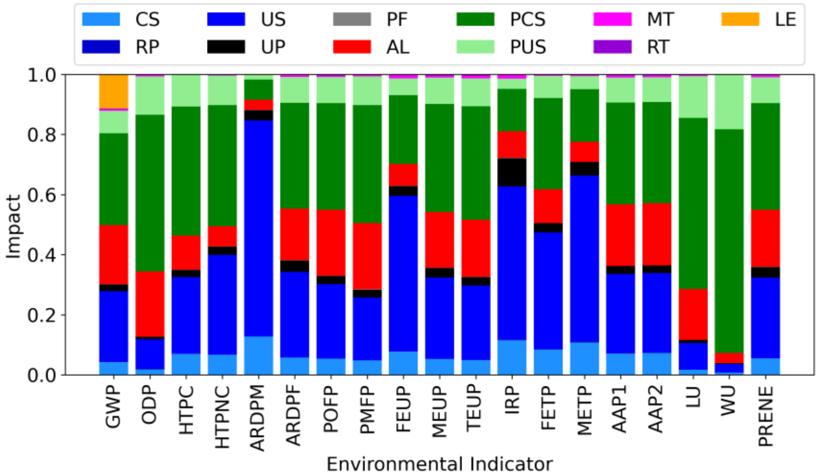
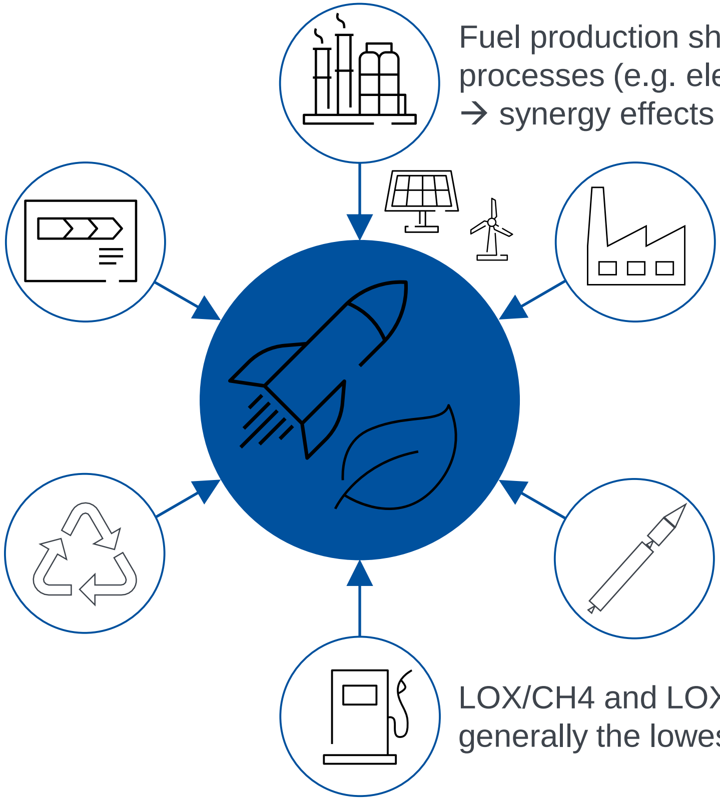


Fig. 35: Share of environmental indicators for reusable systems

- Significant reduction of the influence of the core stage
- Higher influence of fuel production, upper stage production and final integration
- Maintenance and transport to launch site low for reusable systems, but possibly underestimated

Recommendations



Fuel production should be changed to renewable energy & processes (e.g. electrolysis and P2G)
→ synergy effects with other industries

The presented methodology offers a framework for impact calculation in early development phase

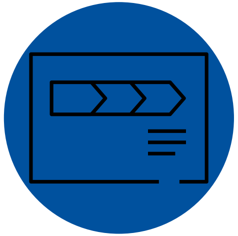
Improve manufacturing of engine, thrust structures and tanks
→ renewable energy

Reusability reduces the impact for most of the environmental indicators depending on return ops

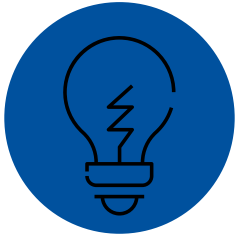
2-stage systems have generally the lowest environmental impact

LOX/CH_4 and LOX/LH_2 systems have generally the lowest environmental impact

Conclusion



- New methodology for simple & fast environmental impact assessment in launcher design
- Results give a good insight into production in Europe
- First study showing the overall impact of launcher production with absolute values



- High impact in production from core stages as well as propellant production
- Reusability reduces environmental impact for most environmental indicators
- Structural factors and subsystem mass distribution required for accurate results

- Significant reduction possible in propellant and dry mass production → change to sustainable production
- Lowest environmental impact for 2 stage systems with LOX/CH4 or LOX/LH2

Acknowledgements

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J.-S. Fischer, S. Fasoulas, C. Brun-Buisson, and E. del Olmo: "*Comparison study on the environmental impact of different launcher architectures*," in Aerospace Europe Conference 2023 - 10th EUCASS - 9th CEAS, Lausanne, Switzerland, 10-14 July 2023 https://doi.org/10.13009/EUCASS2023-274

J.-S. Fischer, S. Fasoulas, C. Brun-Buisson, and E. del Olmo: "*Comparison study on the environmental impact of different launcher architectures*," in 74th International Astronautical Congress (IAC), Baku, Azerbaijan, 2-6 October 2023.

Sources:

[1] Azote for Stockholm Resilience Centre, based on analysis in Persson et al 2022, and Steffen et al 2015

[2] ArianeGroup/ESA: Ariane 6: ESA Space Transportation Program, 2018 url:https://www.eoportal.org/other-space-activities/ariane-6, [14.06.2023]

[3] Tory Bruno. Ula launch vehicle weight and cost by major elements. In Twitter, 01.02.2015.

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

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Thank you!

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