Uncertainty in Life Cycle Assessments of Reusable Launchers:

Preliminary findings

Guillermo J. Dominguez Calabuig
Early Stage Researcher in System Aspects of Reusable Launch Vehicles at German Aerospace Center (DLR) / Visiting researcher University of Strathclyde

Co-authors:

- Andrew Ross Wilsonb, Massimiliano Vasileb, Sifeng Bib. University of Strathclyde
- Martin Sippel. DLR
- Cem Berk Senel, Ozgur Karatekin, Orkun Temel, Royal Observatory of Belgium, Brussels, Belgium

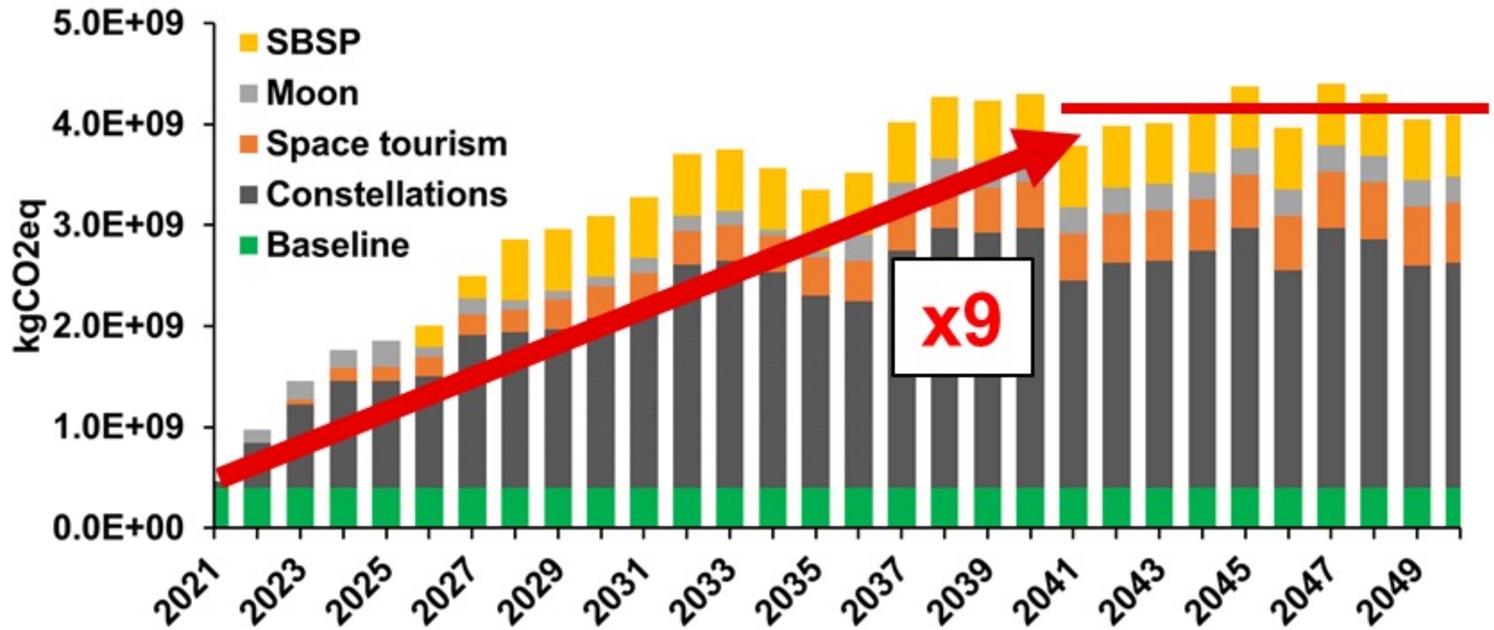
2023 Clean Space Industry Days, 16–19 Oct 2023, ESTEC

DLR · ASCENSION · Marie Skłodowska-Curie Actions · University of Strathclyde Glasgow · ROYAL OBSERVATORY OF BELGIUM

Images credits: SpaceXand OpenAI

Content

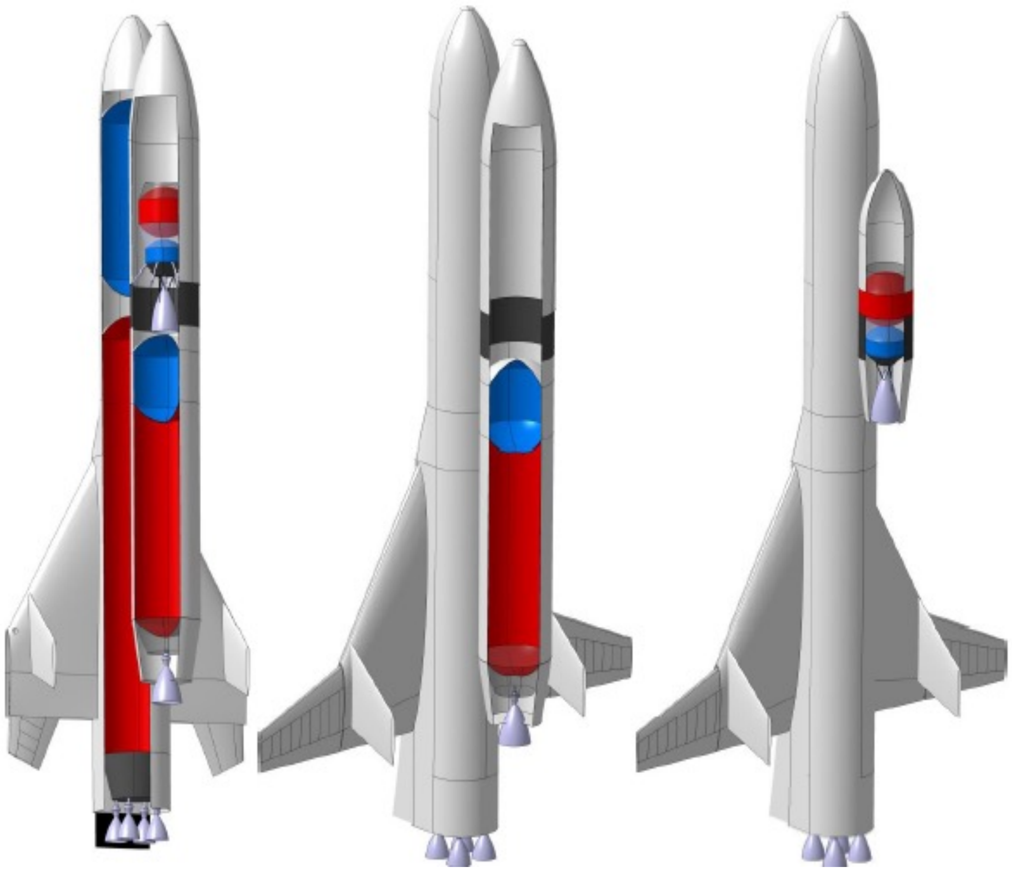
Introduction



CO2 emissions forecast from future proposal space activities [1]

- LCA's being conducted to assess environmental footprint of the space sector [1,2]
  - What are the bottlenecks?
    - Within launcher's life-cycle (excluding launch/reentry)
    - Atmospheric impact from launch-reentry
  - To address these: this presentation shows results from 2 studies
    - LCA of different RLV types
    - Atmospheric impact Black Carbon within LCA

Launch vehicle fleets



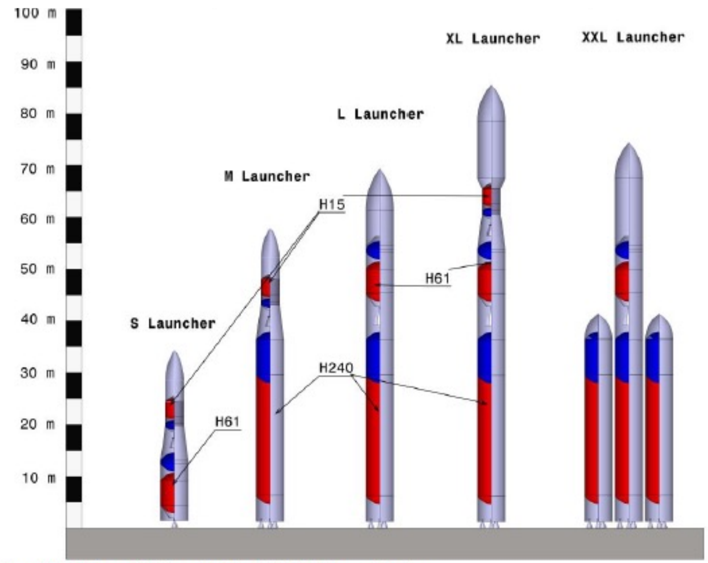


Figure 7: Building-Block launcher family LOX-LH2 combination

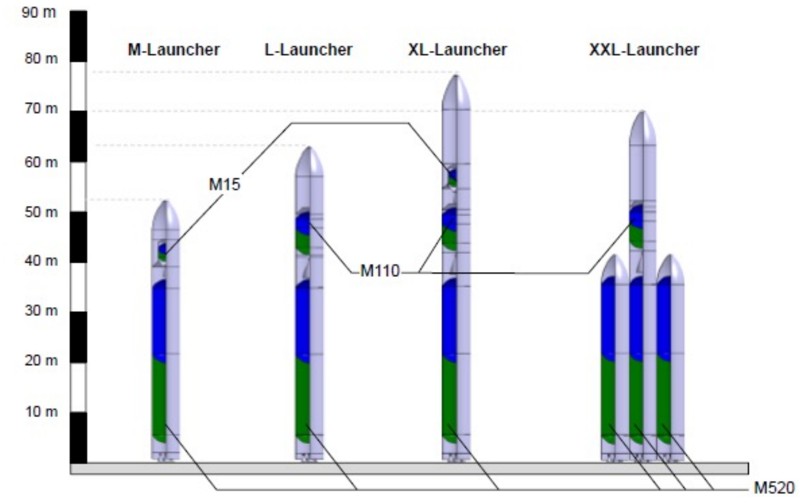
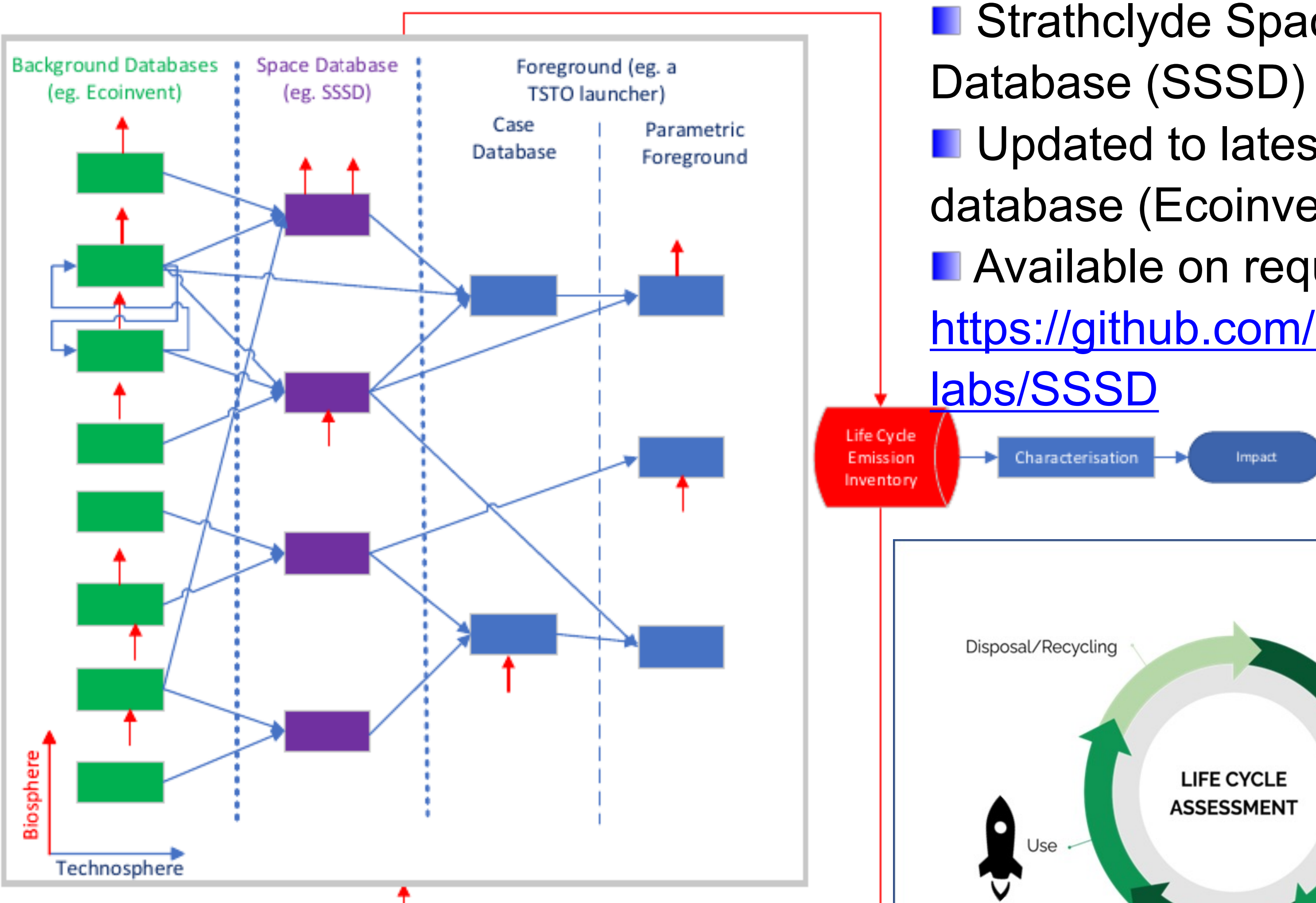


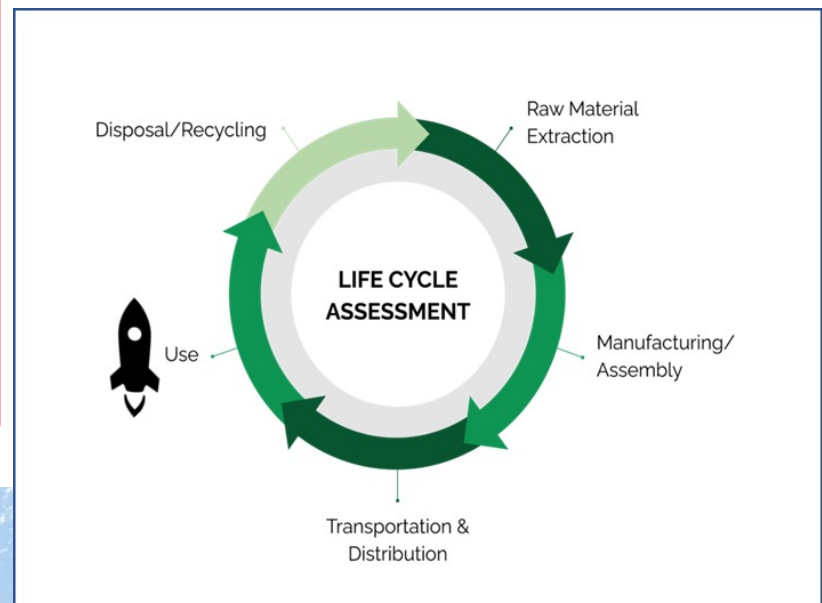
Figure 8: Building-Block launcher family LOX-LCH4 combination

-VTHL RLVC4, VTVL LCH4, VTVL, LH2 families. From [9,10]

LCA Methodology: Space Based SSSD



- Strathclyde Space Systems Database (SSSD)
- Updated to latest background database (Ecoinvent 3.91)
- Available on request on: https://github.com/strath-ace-labs/SSSD



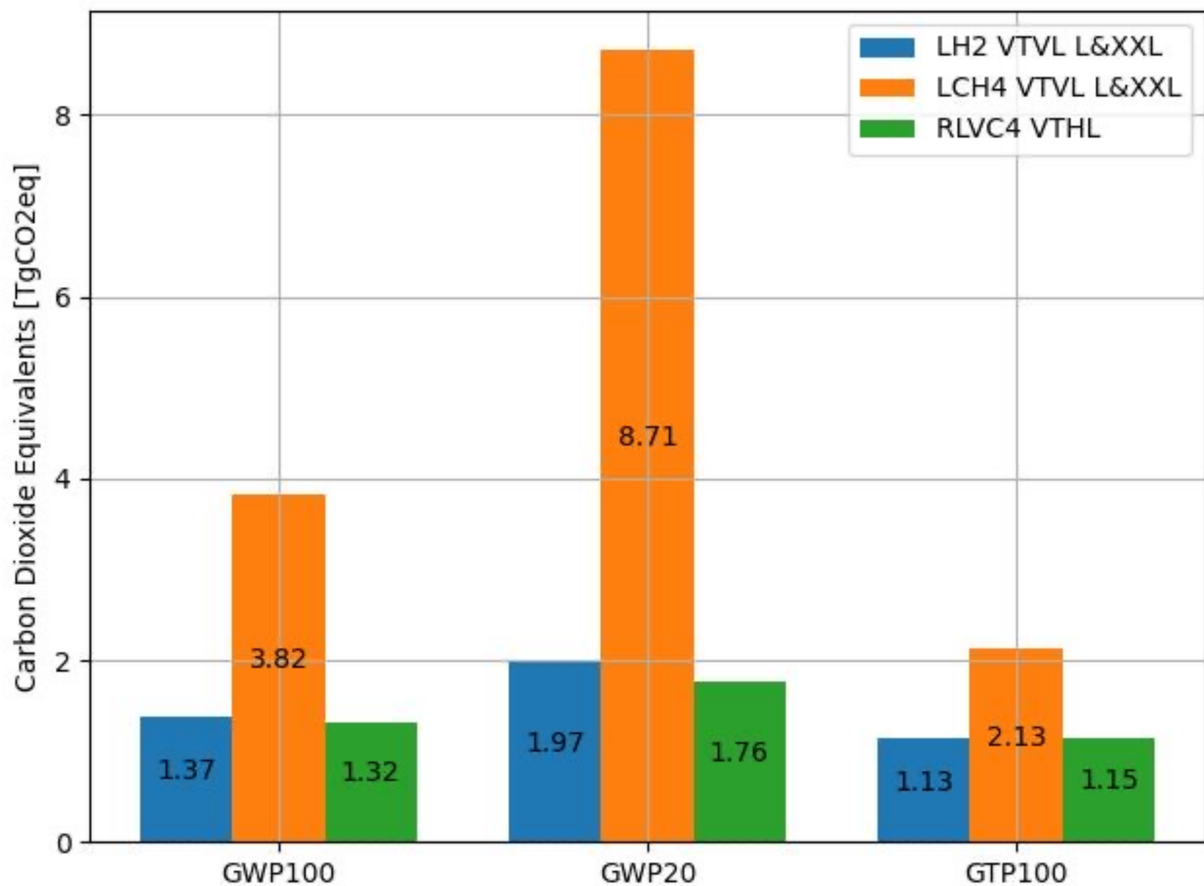
LCA Methodology: Launcher foreground case

- Infrastructure not considered (only recovery specific infrastructure)
- Activities based on proxies:
  - Phase C+D
    - Propellants life cycle
      - Production
      - Clean room fuelling
      - Decontamination
      - General handling
      - Storage
    - Production of launcher components
      - Production of Stage 1 / Common Core+Boosters
      - Production of Stage 2
      - Production of Stage 3
      - Production of Fairing
  - What about allocation of Phase A+D?
    - Dominated by protoypes/test firings/travel
  - Phase E1
    - Assembly, Integration and Testing
    - Launch Campaign
    - Launch Event
  - Phase F
    - Recovery Operations
    - Refurbishment of Stage 1/Boosters

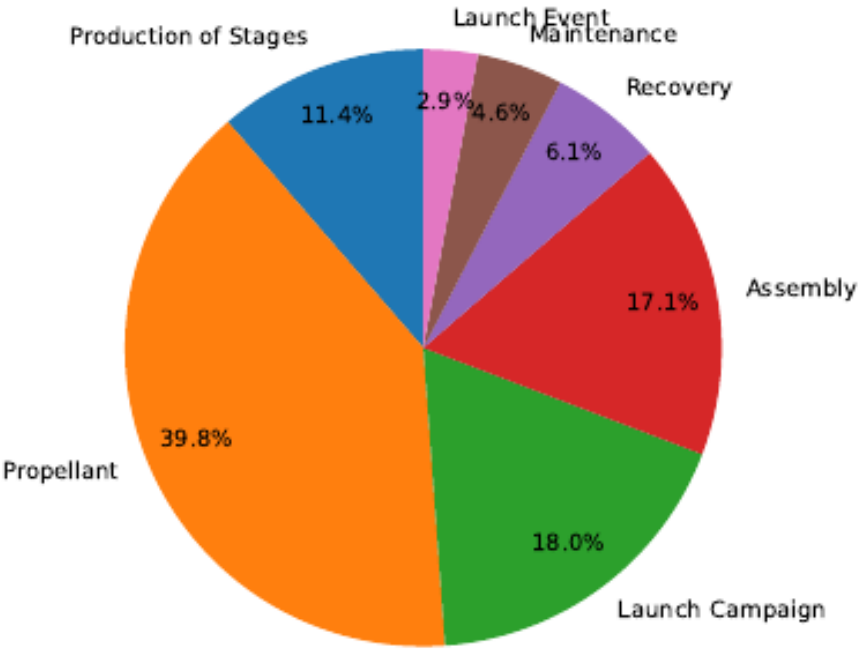
Climate Change Impacts of RLVs: Fleet impacts

- Number of launches from accompany paper
- RLVC4 VTHL lowest impact
- Significant differences between climate metrics
- Assuming ground based emissions result in significantly lower impacts (especially for LCH4 fleet with GWP20)
  - Are these CF's adequately modelling the launcher impact?

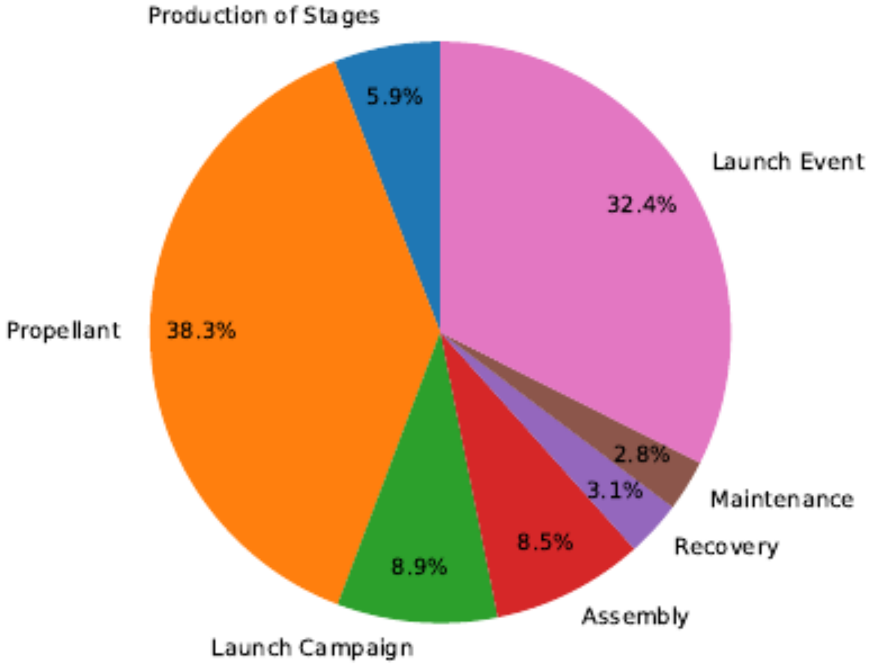
Launcher	n	GWP_{100} $[CO_{2,eq}]$	GWP_{100} [% G.]	GWP_{20} $[CO_{2,eq}]$	GWP_{20} [% G.]	GTP_{100} $[CO_{2,eq}]$	GTP_{100} [% G.]
L-RLV: H240 + H61	55.4	4.73	6.53	4.02	4.68	6.31	4.01
XXL-RLV: 2 H240 + H240 + H61	84.2	7.98	1.4%	11.84	4.9%	6.49	0.2%
XXL-RLV, exp. core.: 2 H240 + H240 + H61	45.9	9.48	1.2%	13.39	4.3%	7.96	0.2%
L-RLV: M520 + M110	61.7	12.08	6.9%	24.87	15.2%	7.58	1.2%
XXL-RLV: 2 M520 + M520 + M110	58.7	23.10	9.9%	55.12	18.7%	12.01	2.1%
XXL-RLV, exp. core.: 2 M520 + M520 + M110	69.0	24.95	9.1%	57.06	18.0%	13.82	1.8%
RLVC4 VTHL Mini-TSTO	39.9	5.93	1.0%	7.97	3.7%	5.13	0.1%
RLVC4 VTHL TSTO	78.0	7.07	1.1%	9.42	4.2%	6.15	0.2%
RLVC4 VTHL 3STO	70.7	7.49	1.1%	9.95	4.1%	6.53	0.2%



Climate Change Impacts of RLVs: Contributional Analysis (GWP100)

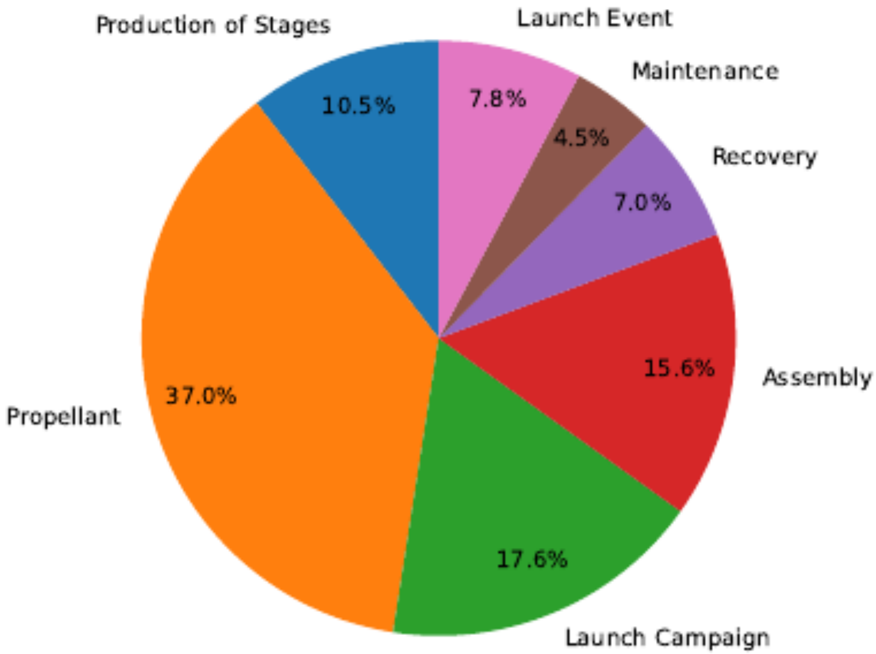


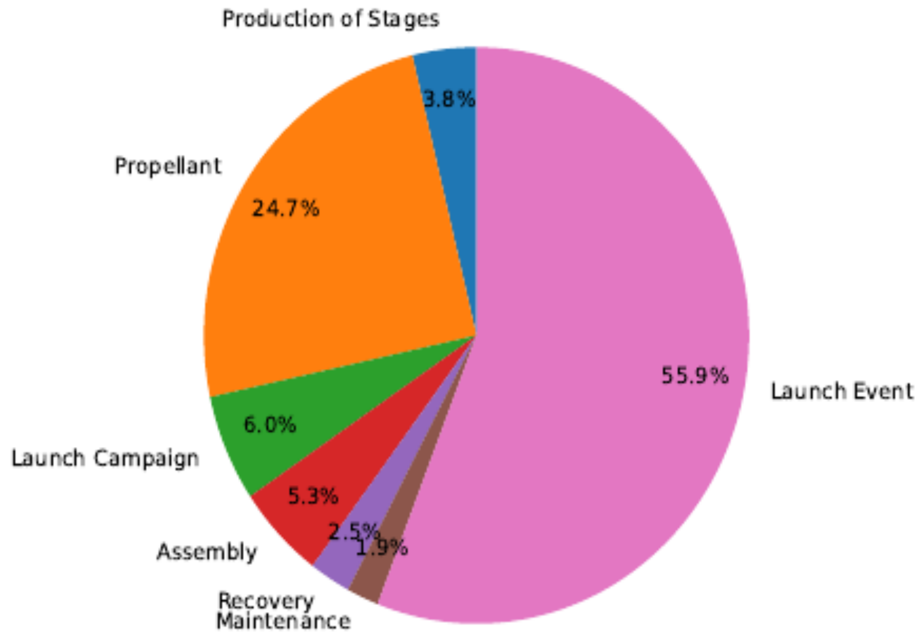
VTVL LH2 (GWP100)



VTVL CH4 (GWP100)

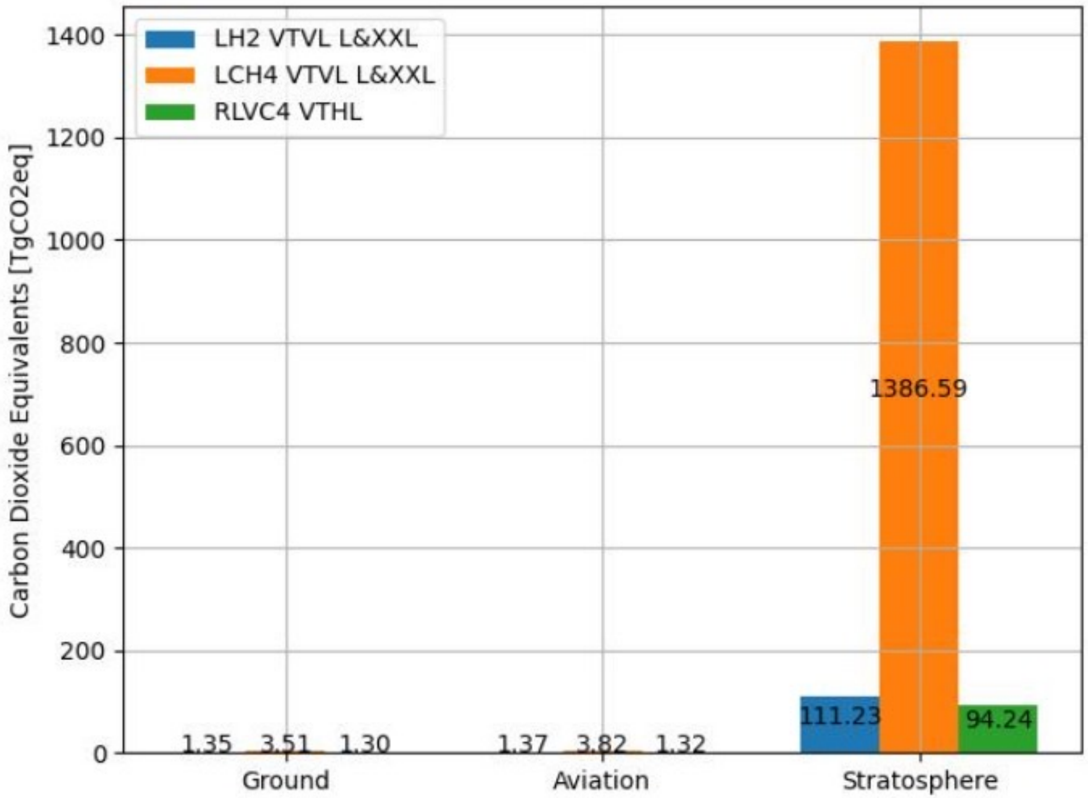
Climate Change Impacts of RLVs: Contributional Analysis (GWP20)

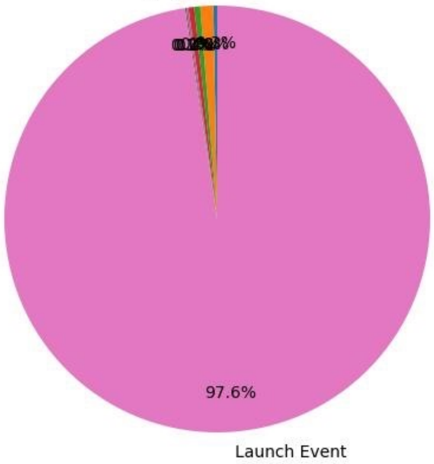




- VTVL LH2 (GWP100)
- VTVL CH4 (GWP20)

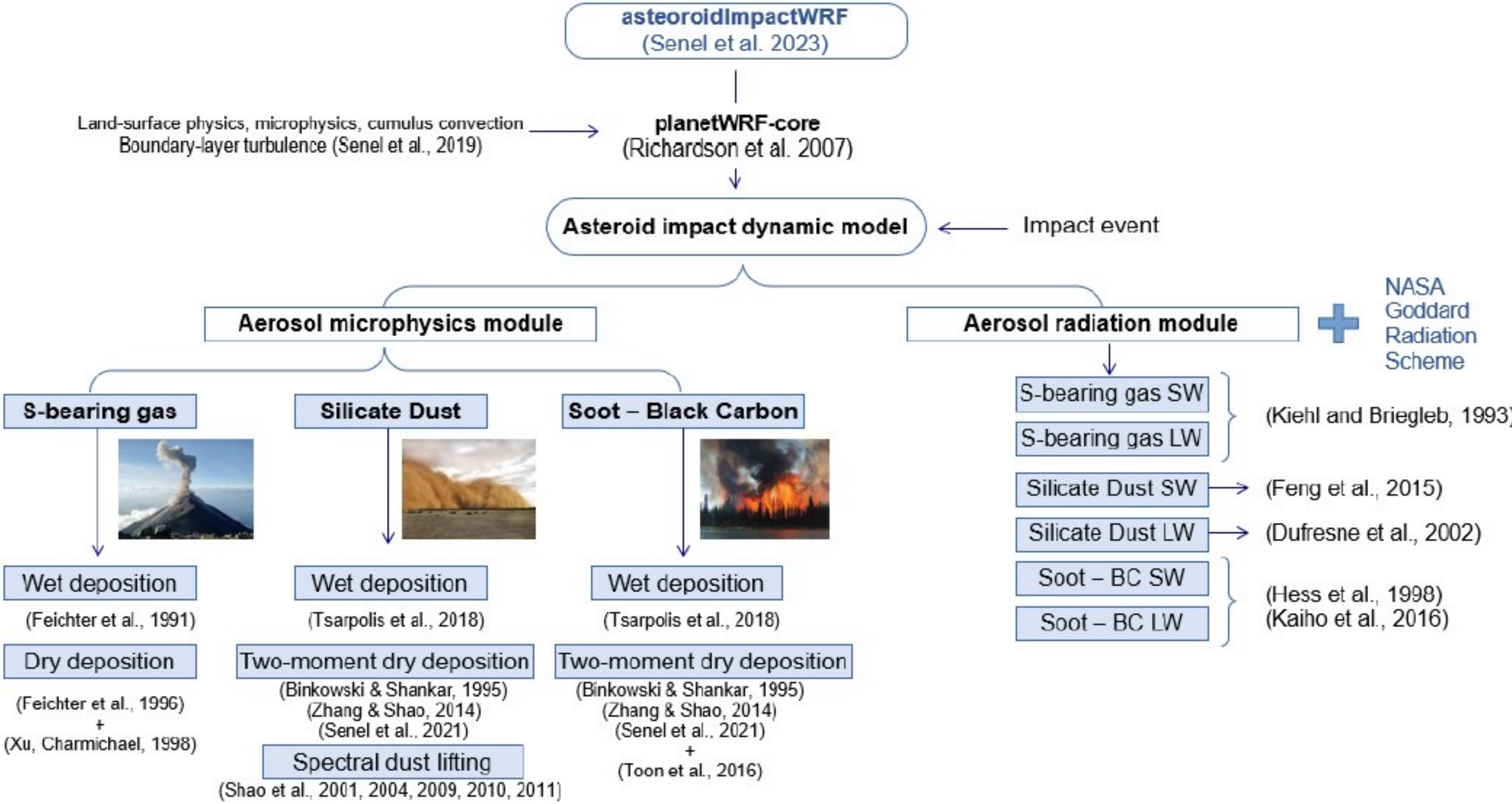
Climate Change Impacts of RLVs: Use of Analogue CFs derived from RF [11]



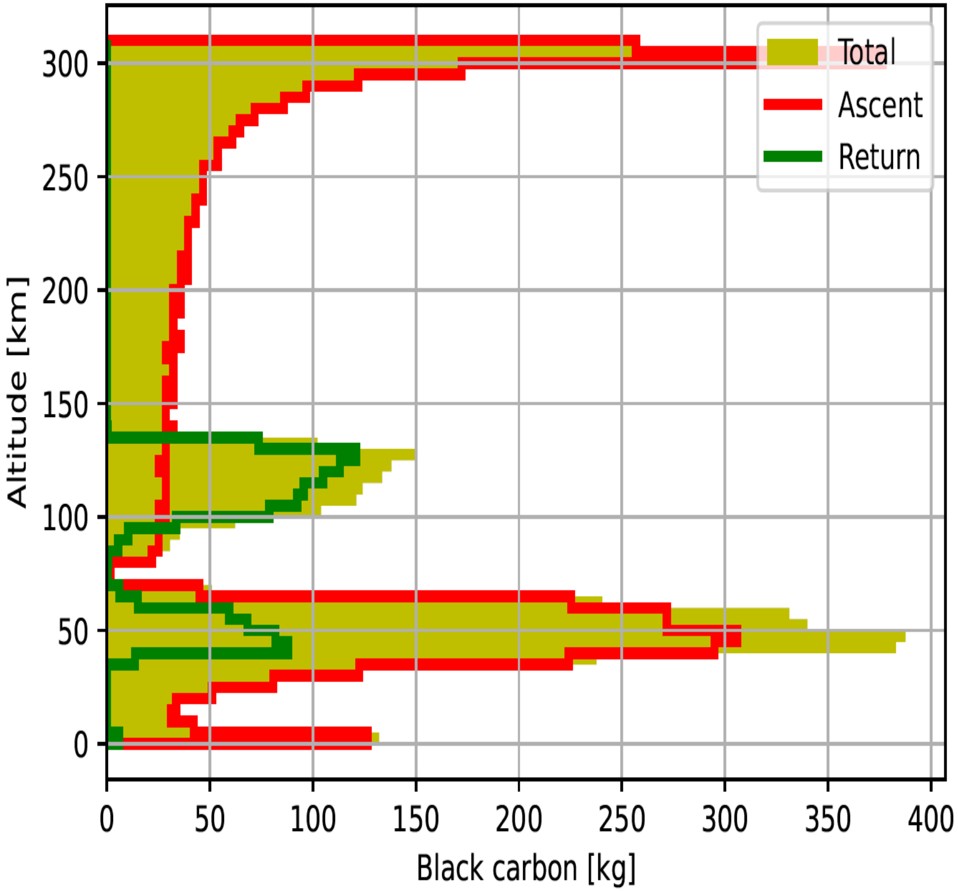


- VTVL LH2 (GWP100) including high altitude impact

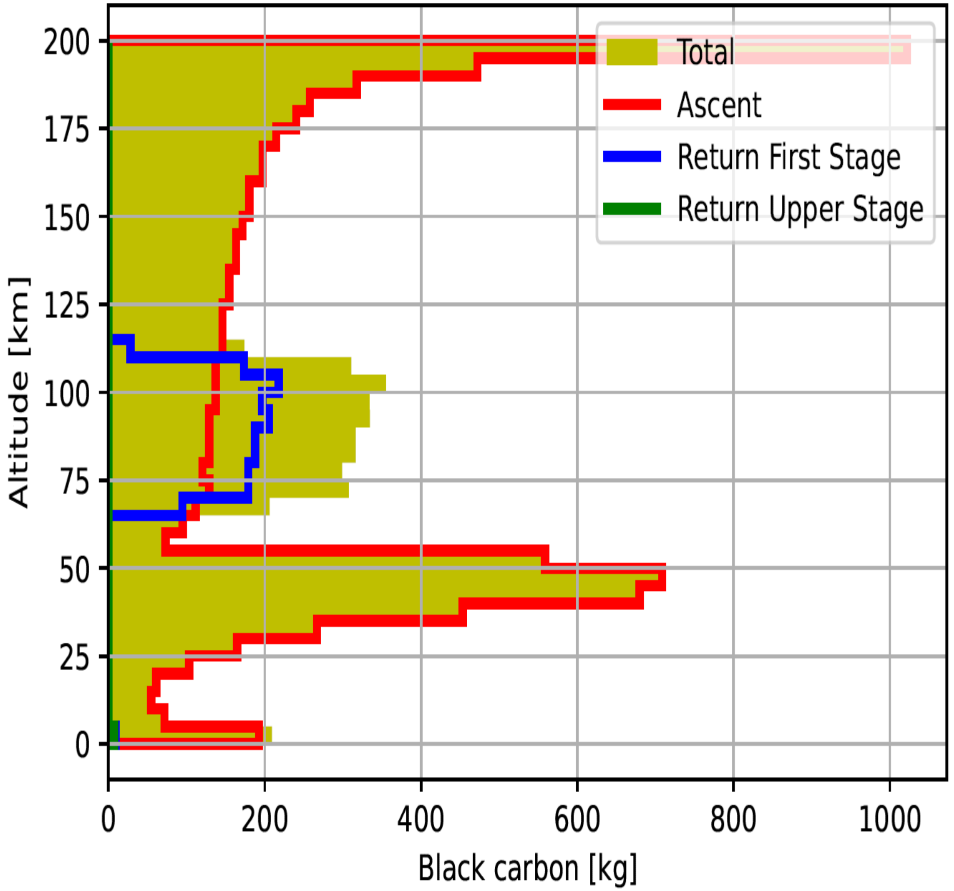
GCM Modelling



GCM Input: Emission profiles

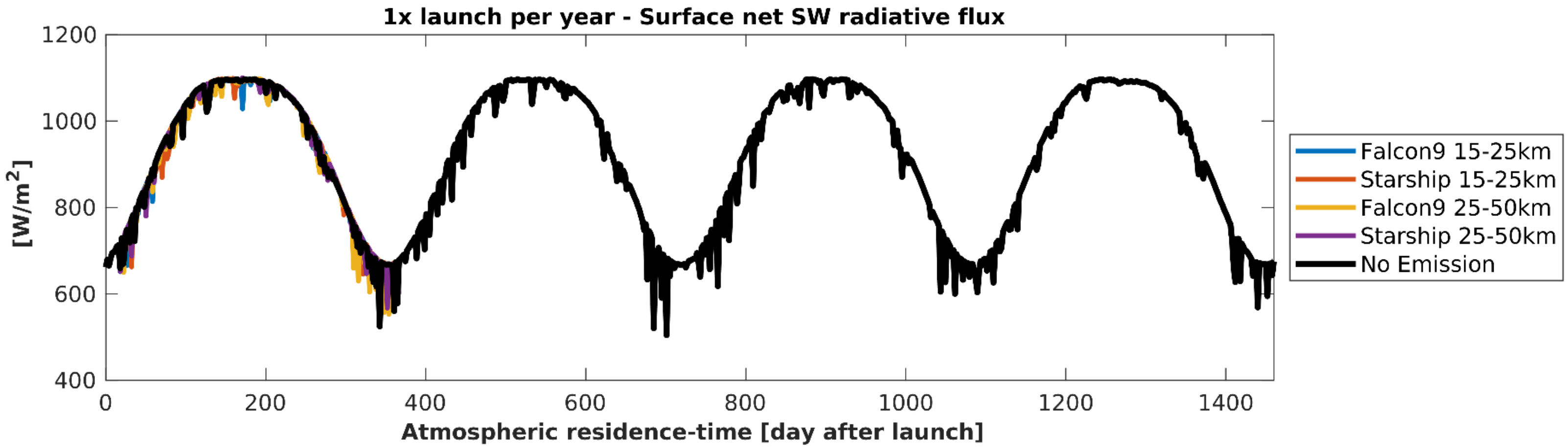


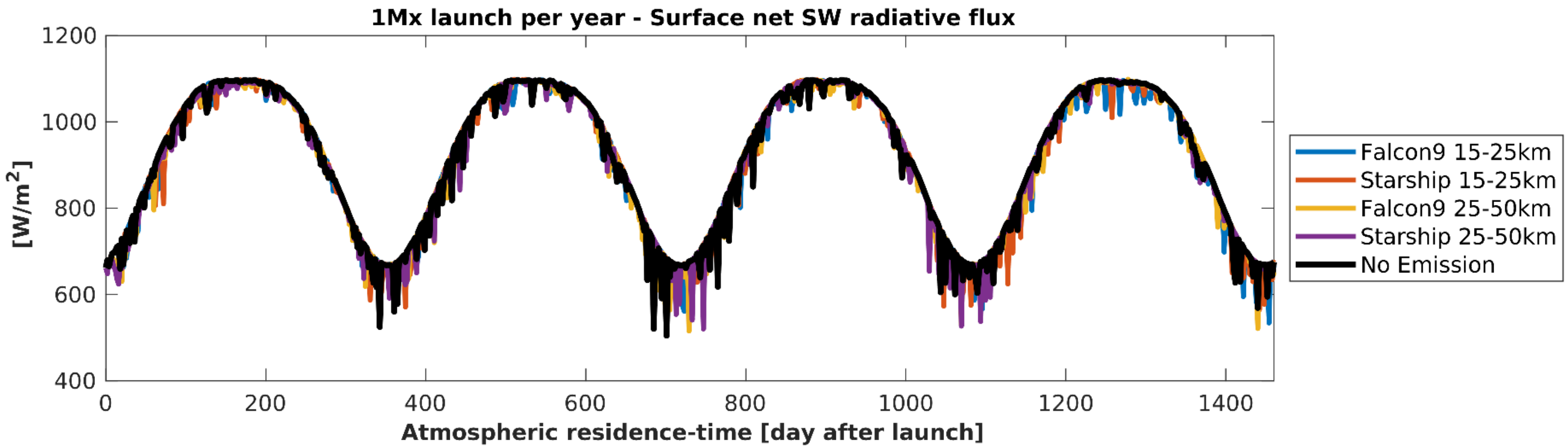
Falcon 9 BC emissions



Starship BC emissions

GCM Results: Radiative Forcing

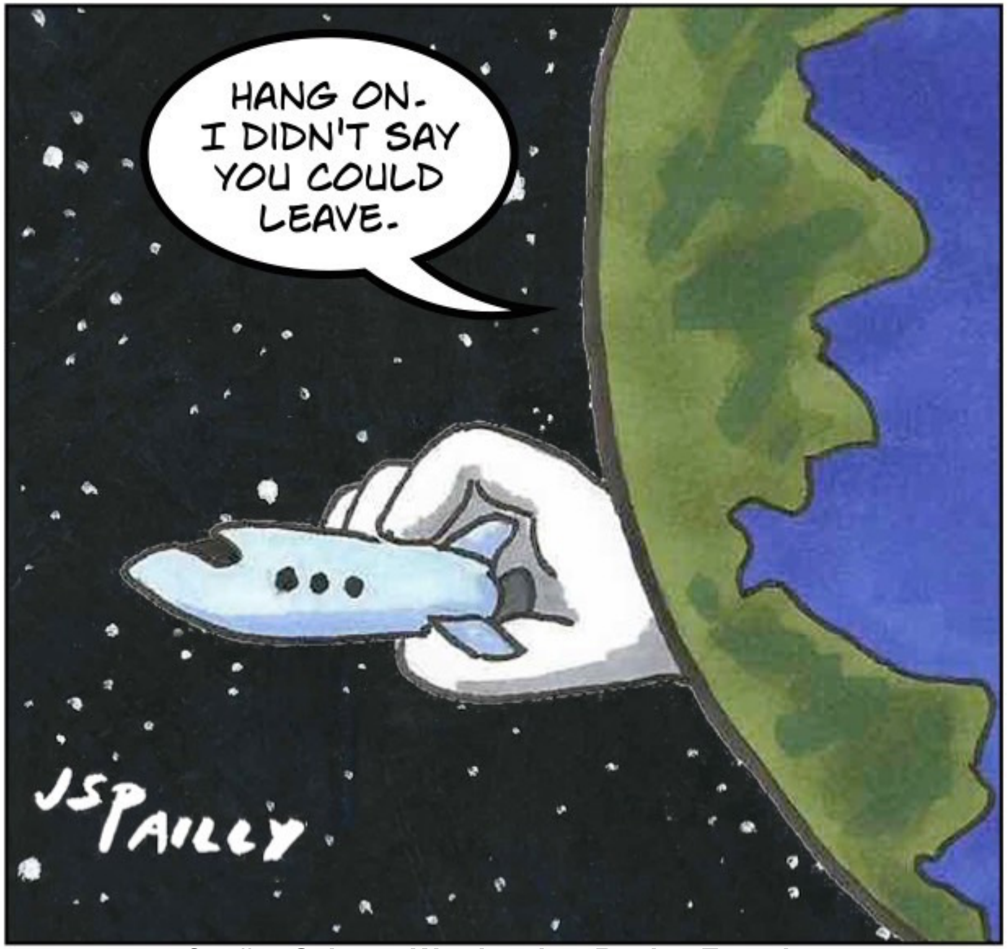




Conclusions

- RLVC4 had the lowest impact (except in GTP100)
  - In-air capturing approach showed lower impact than the sea fleet required within DRL operations
- Launch event impacts appear as a dominating process, specially for the LCH4 fleet and when employing GWP20, because of the non-co2 emissions modelled.
- Uncertainty in results may be completely dominated by high altitude impacts from launch and re-entry emissions when using analogue CFs
  - Significant challenge to incorporate these within LCA's
- Climate simulations ongoing to verify analogue. Currently no major signature identified (different from past studies). Uncertainty in:
  - Reflectivity properties vs wavelength might not be adequate for study case (based on large forest fires)
  - Pulse vs Sustained Emissions
  - Particle size distribution for methalox required
  - Plume post-combustion model
- Future studies shall address these high-altitude impacts, fugitive emissions, and include additional LCI processes as:
  - Launch infrastructure (launch sites/landing sites),
  - Transportation processes
  - Development phases and test firings

Any Questions?



Credits: **Sciency Words: Ideal Rocket Equation**
https://planetpailly.com/2015/04/17/sciency-words-ideal-rocket-equation/

Email: guillermo.dominguezcalabuig@dlr.de

Acknowledgments: Lois Miraux, Andrew R. Wilson, Alberto Sartizu, Cem Berk Senel, ASCenSIon network..

ASCENSION
Advancing Space Access Capabilities – Reusability and Multiple Satellite Injection

European Commission | Horizon 2020 European Union funding for Research & Innovation

EPC European Project Center

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 860956.

Bibliography

(1) Miraux, Loïs; Wilson, Andrew Ross; Dominguez Calabuig, Guillermo J., "Environmental sustainability of future proposed space activities", Acta Astronautica, 2022

(2) Guillermo J. Dominguez Calabuig, Lois Miraux, Andrew Ross Wilson, Alberto Sarritzu, Alberto Passini, "Eco-design of future reusable launchers: insight into their life cycle and atmospheric impact". In 9th European Conference for Aeronautics and Space Sciences (EUCASS), 2022

(3) Ross, M.N. and Sheaffer, P.M. (2014), Radiative forcing caused by rocket engine emissions. Earth's Future, 2: 177-196. DOI: 10.1002/2013EF000160

(4) Martin N. Ross, Karen L. Jones, Implications of a growing spaceflight industry: Climate change, Journal of Space Safety Engineering, Volume 9, Issue 3, 2022, Pages 469-477, ISSN 2468-8967, https://doi.org/10.1016/j.jsse.2022.04.004.

(5) Ryan, R. G., Marais, E. A., Balhatchet, C. J., & Eastham, S. D. (2022). Impact of rocket launch and space debris air pollutant emissions on stratospheric ozone and global climate. Earth's Future, 10, e2021EF002612. https://doi.org/10.1029/2021EF002612J.

(6) Maloney, C. M., Portmann, R. W., Ross, M. N., & Rosenlof, K. H. (2022). The climate and ozone impacts of black carbon emissions from global rocket launches. Journal of Geophysical Research: Atmospheres, 127, e2021JD036373. https://doi.org/10.1029/2021JD036373

(7) Leonard Schulz, Karl-Heinz Glassmeier, "On the anthropogenic and natural injection of matter into Earth's atmosphere", Advances in Space Research, Vol. 67, Issue 3, 2021, Pages 1002-1025, ISSN 0273-1177, DOI: 10.1016/j.asr.2020.10.036.

(8) Pletzer, J. and Hauglustaine, D. and Cohen, Y. and J\"ockel, P. and Grewe, V., The climate impact of hydrogen-powered hypersonic transport, Atmospheric Chemistry and Physics, Vol 22, 2022, Number 21, DOI: 10.5194/acp-22-14323-2022

(9) Jascha Wilken. Cost estimation for launch vehicle families considering uncertain market scenarios. In ASCenSIon Conference, Dresden, 12-14th September, 2023., 2023

(10) Martin Sippel, Steffen Callsen, Jascha Wilken, Kevin Bergmann, Ingrid Dietlein, Loenid Bussler, Guillermo Joaquin Dominguez Calabuig, and Sven Stapper. Outlook on the new generation of european reusable launchers. In ASCenSIon Conference, Dresden, 12-14th September, 2023, 2023.

(11) Lois Miraux. Derivation of analog gwp coefficients for the high altitude effects of launches. In Workshop on Life Cycle Assessment of Space Transportation Systems, 4-6 July, 2023, Stuttgart,, 2023.

Appendix: LCIA methods

Table 2: Climate change life cycle impact for a kg of emission. Values from IPCC [24] for ground based emissions and Lee et al [25] unless otherwise stated.

Species	GWP_{100}		GWP_{20}		GTP_{100}		Reference
	Aviation	Ground	Aviation	Ground	Aviation	Ground	
H_2O	6×10^{-2}	5×10^{-4}	0.22	-1×10^{-3}	0.008	0.	[26]
NO_x	114	8.5	619	31.5	13	−0.65	[27]
H_2	12.8	12.8	40.1	40.1	2.3	2.3	[28]
CH_4	29.8	29.8	82.5	82.5	7.5	7.5	
CO	4.0	4.0	9.2	9.2	1.95	1.95	
BC	1166	900	4288	3200	161	130	

- LCIA
  - Global Warming Potential over 100 years (GWP100)
  - Global Warming Potential over 20 years (GWP20)
  - Global Temperature Change Potential over 100 years (GTP100)
- Aviation based impact factors assumed as default for the assessment
  - Sensitivity was performed with ground based emissions

Appendix: Past studies and climate metric derivation for LCA's

- Based on [11]
- From instantaneous stratospheric radiative forcing (A):

$$RF_i(t) = A_i\, R_i(t)$$

  - Not TOA or Tropopause, nor RF or ERF
- Assumes exponential decay

$$R_i(t) = e^{-\frac{t}{\tau_i}}$$

  - Lifetime assumed from averaged stratospheric circulation
  - Where does it sink?

Table 1: Instantaneous stratospheric Radiative Forcing A for emissions of different species in the stratosphere obtained from past studies

Species	A_i (W/m^2/Tg)			
	Ross et al.[3]	Ryan et al,[5]	Pletzer et al,[8]	This study
BC	34 300	8720		34 300
H2O	31.8	−24.0	1.58, 1.90	31.8
Al2O3	6000			6000
CO2	0.017			0.017
NOx				
Cloudiness				

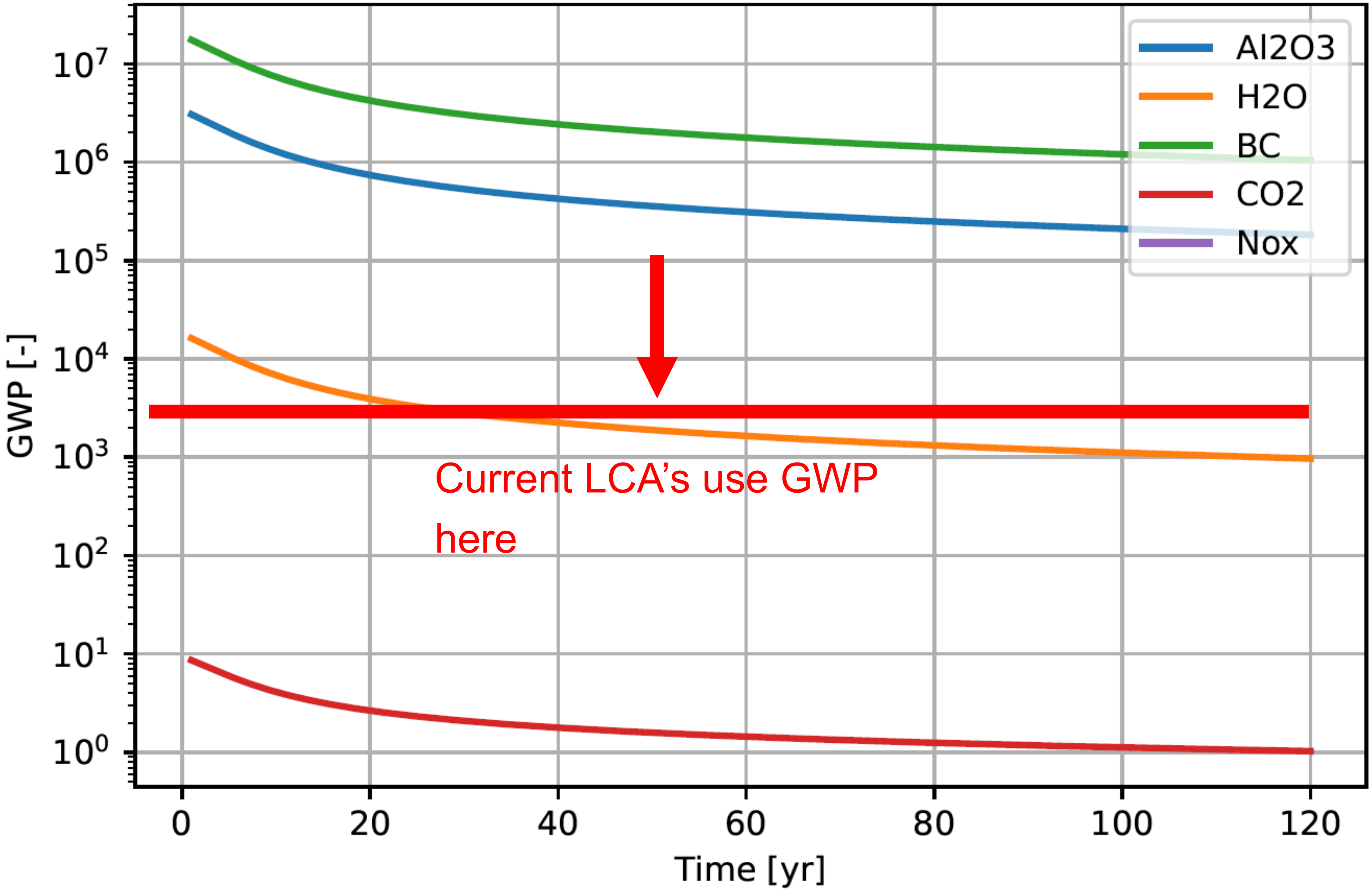
- Absolute Global Warming Potential:

$$AGWP_i(H) = \int_0^H RF_i(t)dt = A_i\tau_i\left(1 - e^{-\frac{t}{\tau_i}}\right)$$

- Global Warming Potential

$$GWP_i(H) = \frac{AGWP_i(H)}{AGWP_{CO_2}(H)}$$

Appendix: Past studies and climate metric derivation for LCA's



Appendix GCM Results Residence Time