ORBEX

University of Exeter
Environment and Sustainability Institute

Imperial College London
Consultants

# Ultra-Green Launch & Space Transportation Systems Study

The activities were carried out under a programme of and funded by the European Space Agency

esa

# Contents

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Faculty of Environment, Science and Economy

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Faculty of Engineering, Department of Civil and Environmental Engineering

# Overview

- Consideration of project terminology “Ultra-Green”
- Launch system performance metric defined as **kg $CO_2$e/kg payload**
- Radiative Forcing of non-$CO_2$ emissions at high altitude were taken into account, with a special focus on <u>black carbon</u>

# Investigated Launch Vehicle Classes

| | Class 1: Microlauncher / Demonstrator | Class 3: Intermediate | Class 4: Heavy/Super Heavy |
|---|---|---|---|
| Payload [kg] | 150 | 8000 | 100000 |
| Launch Site | Kourou | | |
| Target Orbit | 500km, 55 deg | | |

# Method Overview

**Orbex**
Engine design
Launch Vehicle Design
BOMs
CAD & AEDB
Trajectory Generation

→

**Imperial College**
Atmospheric aerosol environmental effects
Black Carbon effects

→

**University of Exeter**
Environmental Lifecycle Analysis

# Completed Reference Rocket Architecture Matrix

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| 3 | **Propellant** | **CFRP** | **Alu** | **CFRP** | **Alu** | **Stainless** | **Alu** | **Stainless** |
| 4 | Propane/LOX | Length 19.72 m<br>Wet Mass 24683.2095 kg<br>Dry Mass 1960.9722 kg<br>S1 engines 8 | Length 23.89 m<br>Wet Mass 32067.3181 kg<br>Dry Mass 2638.2645 kg<br>S1 engines 10 | Length 57.70 m<br>Wet Mass 389056.6415 kg<br>Dry Mass 18378.6271 kg<br>S1 engines 5 | Length 62.16 m<br>Wet Mass 441620.5297 kg<br>Dry Mass 24580.9636 kg<br>S1 engines 6 | Length 76.51<br>Wet Mass 611720.9594 kg<br>Dry Mass 45651.4147 kg<br>S1 engines 8 | Length 90.49 m<br>Wet Mass 4986692.35 kg<br>Dry Mass 286787.172 kg<br>S1 engines 29 | Length 115.29 m<br>Wet Mass 7211992.12 kg<br>Dry Mass 550992.5332 kg<br>S1 engines 42 |
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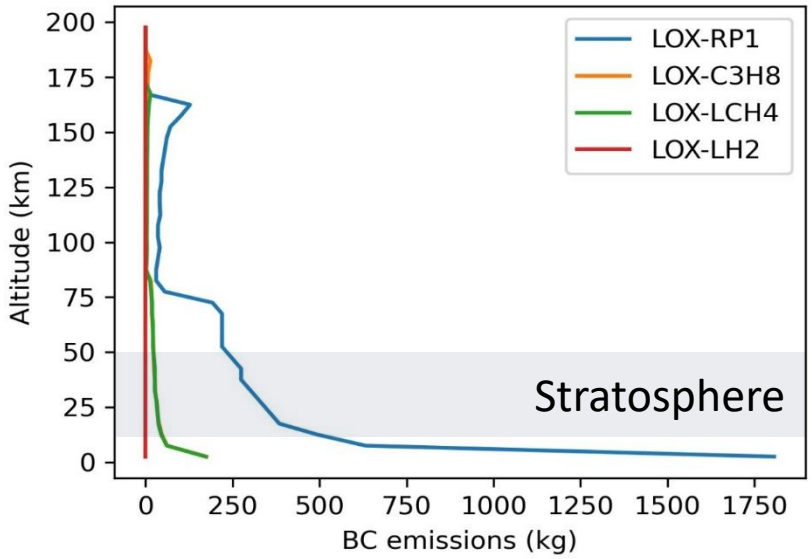
# Black Carbon: Trajectory Analysis

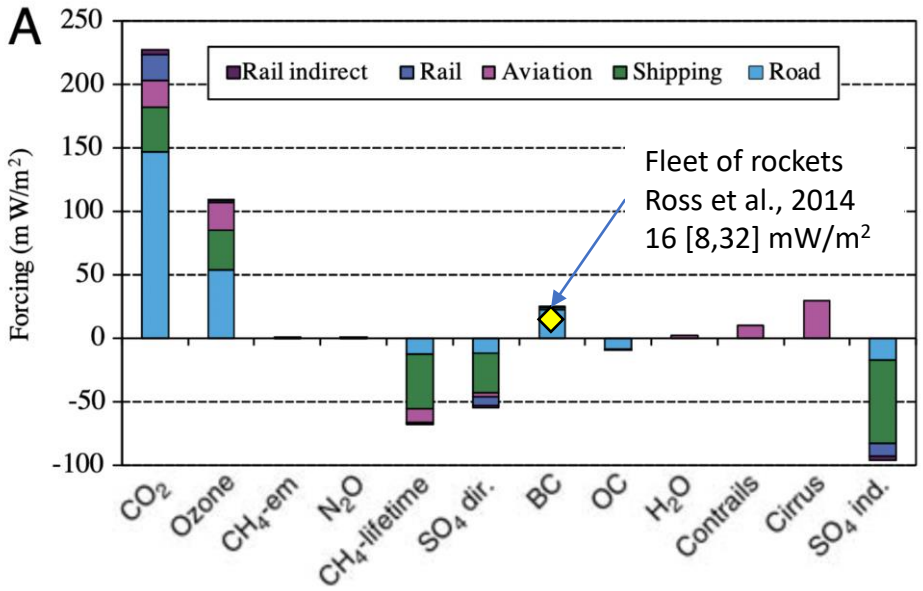
- The figure opposite shows an example result of the distribution of BC emissions in the atmosphere resulting from the four different propellants for a launch vehicle of constant class and construction material.
- The altitude of the stratosphere is indicated on the graph (~12-50 km)
- Note: LOX-C3H8 and LOX-CH4 are overlapping due to equivalent emissions index
- The table shows the class 3 black carbon $CO_2e/CO_2$ due to the black carbon emission in the stratosphere

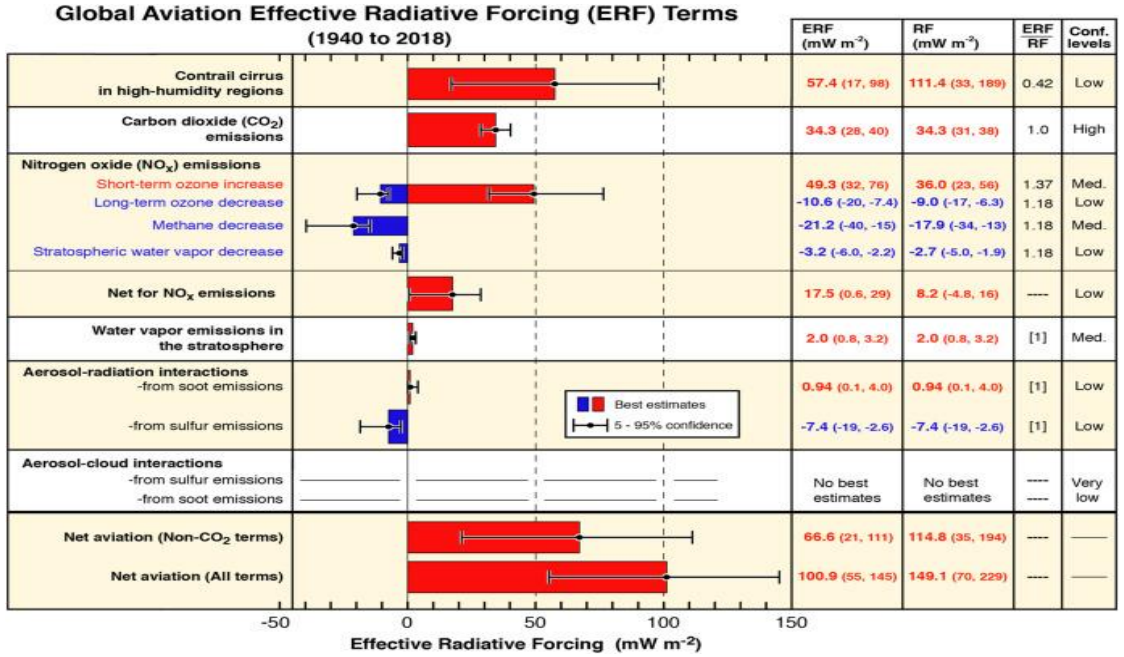



| Class 3 (Intermediate) | Time Horizon | Ratio: BC $CO_2e/CO_2$ | | |
|---|---|---|---|---|
| | | CFRP | Aluminium | Stainless |
| | | Nominal | Nominal | Nominal |
| **Propane/LOX** | 100 | 1443 | 1437 | 1429 |
| **$H_2$/LOX** | 100 | - | - | - |
| **$CH_4$/LOX** | 100 | 1185 | 1184 | 1177 |
| **RP1/LOX** | 100 | 13478 | 13552 | 13431 |

# Comparison to other transport modes

- For other transport modes, the climate forcing of $CO_2$ dominates relative to direct warming due to BC
- For aviation, secondary effects of BC on contrails and contrail cirrus are of the same order of magnitude as $CO_2$
- The large ratio of BC $CO_2e/CO_2$ for some concepts is due to very high BC emissions (relative to other concepts, e.g. LOX-RP1) and higher BC GWP relative to other modes of transport
- Previous estimate of RF due to a fleet of rockets (Ross et al., 2014) suggests the RF may be 15% of aviation RF, and that this is almost all due to BC





Fuglestvedt et al. (2007) Climate forcing from the Transport Sectors. PNAS. https://www.pnas.org/doi/full/10.1073/pnas.0702958104
Lee et al. (2021) The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment. https://doi.org/10.1016/j.atmosenv.2020.117834
Ross, M.N. and Sheaffer, P.M., 2014. Radiative forcing caused by rocket engine emissions. *Earth's Future*, *2*(4), pp.177-196.

# Final LCA results – total emissions per launch

| t CO2 eq/launch (without BC high altitude GWP100) | Class 1 (Micro) | | Class 3 (Intermediate) | | | Class 4 | |
|---|---|---|---|---|---|---|---|
| | CFRP | Alu | CFRP | Alu | Stainless | Alu | Stainless |
| Biopropane from waste | 72 | 97 | 1,065 | 1,213 | 1,612 | 15,070 | 20,272 |
| Grey methane | 78 | 99 | 1,253 | 1,427 | 1,956 | 17,356 | 24,120 |
| Grey hydrogen | 58 | 73 | 991 | 1,130 | 1,547 | 11,709 | 14,429 |
| Grey RP-1 | 74 | 93 | 1,003 | 1,167 | 1,595 | 15,182 | 20,432 |

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|---|---|---|---|---|---|---|---|
| | CFRP | Alu | CFRP | Alu | Stainless | Alu | Stainless |
| Biopropane from waste | 8,602 | 12,097 | 167,065 | 183,213 | 252,612 | 2,095,071 | 2,940,272 |
| Grey methane | 8,148 | 10,399 | 164,253 | 183,427 | 257,956 | 2,067,356 | 3,044,120 |
| Grey hydrogen | 58 | 73 | 991 | 1,130 | 1,547 | 11,709 | 14,429 |
| Grey RP-1 | 96,474 | 128,093 | 1,611,003 | 1,811,167 | 2,831,595 | 23,115,182 | 33,620,432 |

- **When considering black carbon radiative forcing at high altitude, total GWP of one launch increases dramatically**
- When black carbon is not considered, conclusions can be drawn on the GWP variance due to different propellant types
- When considering black carbon, biopropane and grey methane are 90-92% lower and grey hydrogen is nearly 100% lower than grey RP-1.
- Alu increases CO2e by 10-41% compared with CFRP (class 1 & 3) while stainless steel increases CO2e by 23-56% compared with Alu (class 3 & 4)

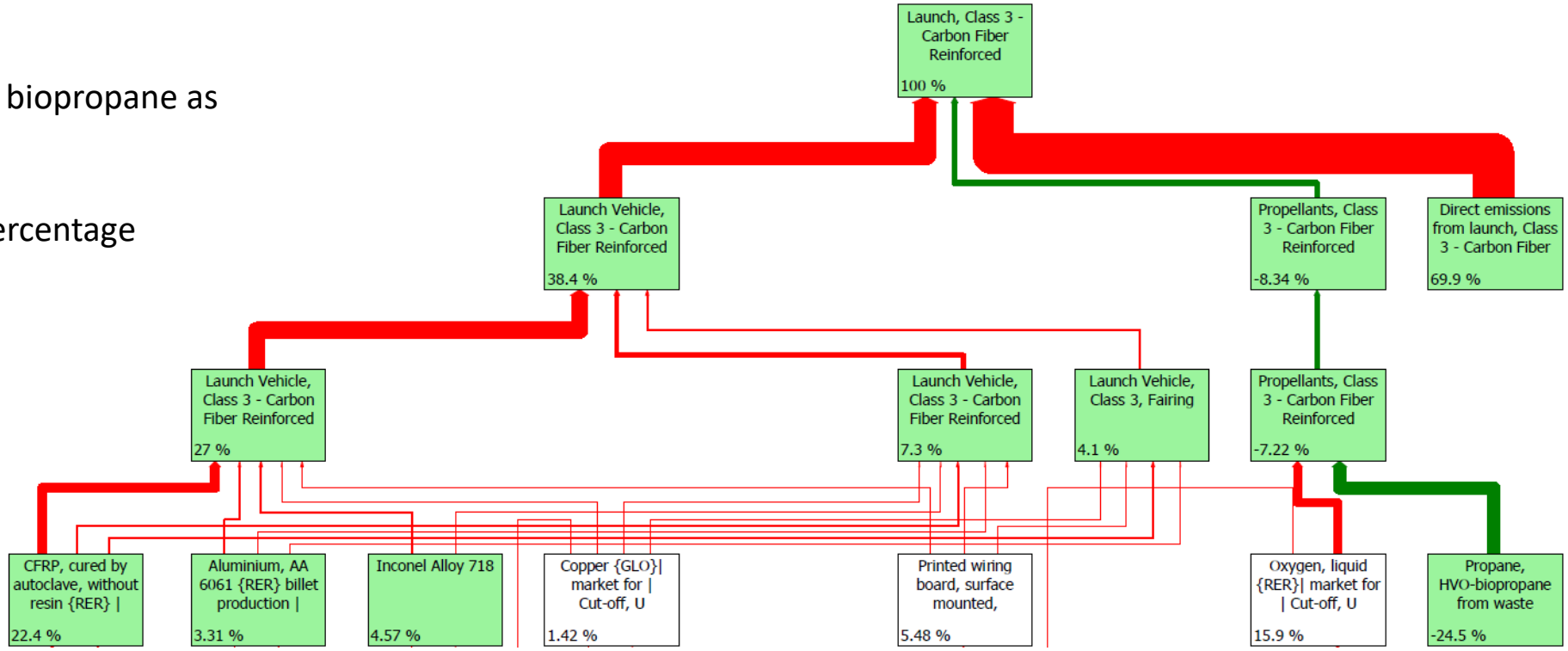
# Final LCA results – emissions by life cycle stage

| Life Cycle Stage | % Contribution to LCA Emissions | | | |
|---|---|---|---|---|
| | Grey Hydrogen | Grey Methane | Biopropane | Grey RP1 |
| Propellant Production | 63 - 72 | 19 - 22 | - (8 – 10) | 22 - 27 |
| Launch Vehicle Manufacture | 28 - 37 | 33 - 44 | 38 - 51 | 42 - 53 |
| Direct Emissions during Launch | - | 37 - 44 | 59 - 71 | 25 - 31 |

- Propellant type is the factor that influence the emissions breakdown by life cycle stage the most.
- As launch vehicle size increases, the share of launch vehicle manufacture in total emissions goes down slightly.
- Different materials for the main rocket structure don't seem to have a significant effect on the emissions breakdown, when black carbon effects are considered.

# Final LCA results – emissions by life cycle stage

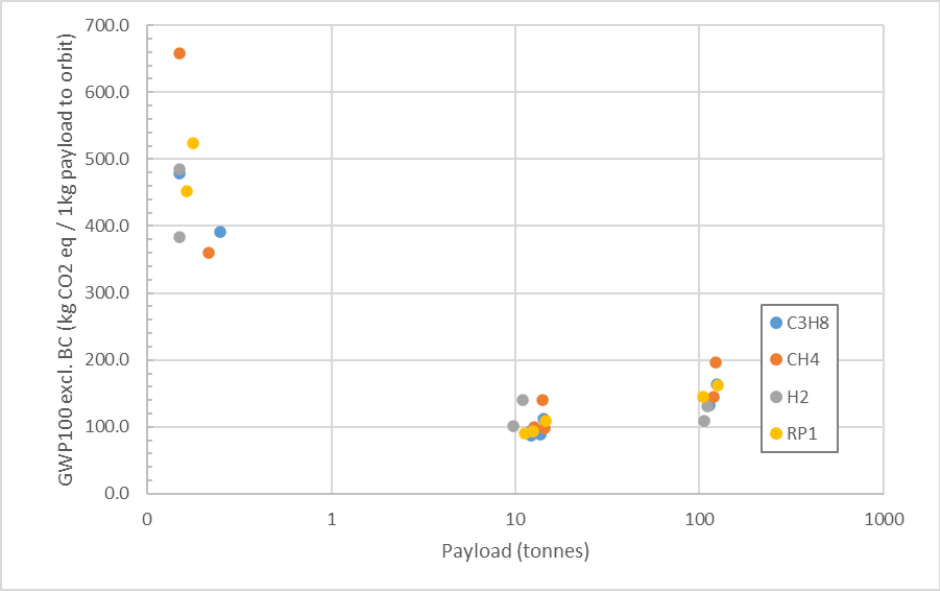
- More details on the processes that contribute most to the total life cycle emissions
- Class 3 CFRP rocket fuelled by biopropane as an example
- The line thickness indicates percentage contribution to the emissions



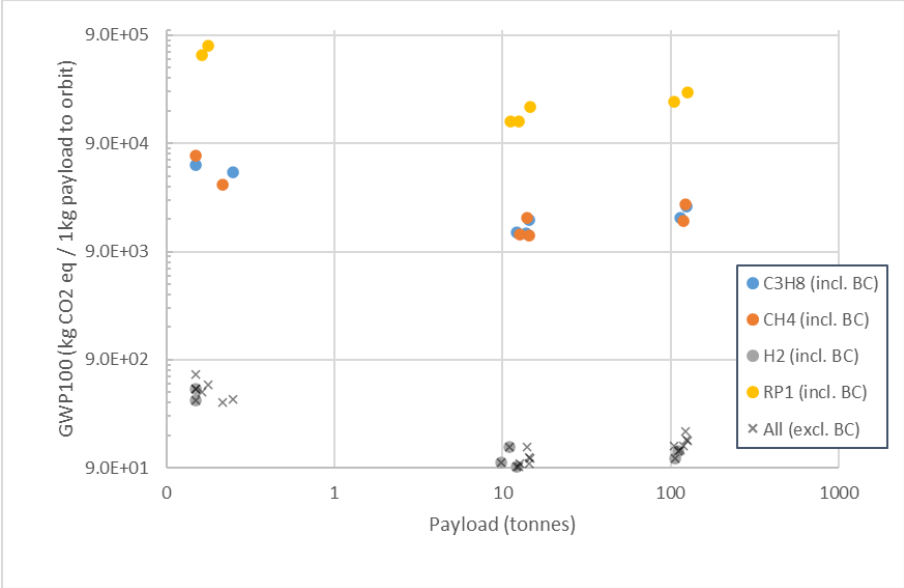
# Final LCA results – emissions/kg of payload deployed

- Normalizing the CO2e by the payload delivered to orbit enables a fair comparison of the relative environmental impact of different vehicle architectures
- Including BC emissions it is clear that:
  - RP1 has highest BC emissions, and therefore the highest total GWP100
  - No BC from H2 meaning that this is the propellant with lowest environmental impact*
  - The GWP100 between C3H8 and CH4 is comparable and sits between H2 and RP1

## Excluding Black Carbon Effects




## Including Black Carbon Effects




** Radiative forcing of H2O emissions in upper atmosphere has not been considered and should also be assessed*

# Final LCA results – Correlation Coefficients

- Pearson correlation coefficients between different subsets of the architectures and various factors were analysed
- These correlation coefficients vary between -1 and 1 where a value of 0 indicates no correlation, 1 a strong positive correlation, and -1 a strong negative correlation

| | | | Excluding BC | | | | | | Including BC | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Nominal Payload | Achieved Payload | S1 Engine Number | TTWR | S1 Structural Fraction | S2 Structural Fraction | Nominal Payload | Achieved Payload | S1 Engine Number | TTWR | S1 Structural Fraction | S2 Structural Fraction |
| | Class | 1 | | -0.52 | 0.35 | 0.41 | -0.07 | 0.06 | | -0.06 | 0.54 | -0.11 | 0.54 | -0.32 |
| | | 3 | | 0.09 | 0.27 | 0.22 | 0.84 | 0.85 | | 0.17 | 0.47 | -0.41 | -0.24 | -0.21 |
| | | 4 | | 0.74 | 0.86 | -0.47 | 0.31 | 0.45 | | 0.09 | 0.54 | -0.14 | -0.17 | -0.05 |
| | Fuel | C3H8 | -0.33 | -0.35 | -0.15 | -0.30 | 0.70 | 0.89 | -0.32 | -0.34 | -0.14 | -0.31 | 0.73 | 0.91 |
| | | CH4 | -0.30 | -0.33 | -0.15 | 0.02 | 0.65 | 0.91 | -0.28 | -0.31 | -0.12 | 0.00 | 0.67 | 0.91 |
| | | H2 | -0.44 | -0.46 | -0.30 | -0.21 | 0.67 | 0.97 | -0.44 | -0.46 | -0.30 | -0.21 | 0.67 | 0.97 |
| | | RP1 | -0.34 | -0.36 | -0.17 | 0.31 | 0.57 | 0.93 | -0.31 | -0.33 | -0.13 | 0.35 | 0.53 | 0.95 |
| | Material | Alu | -0.47 | -0.50 | -0.23 | -0.15 | 0.75 | 0.89 | -0.47 | -0.20 | 0.07 | -0.13 | 0.06 | 0.24 |
| | | CFRP | -0.98 | -0.97 | 0.61 | 0.23 | 0.50 | 0.88 | -0.98 | -0.34 | 0.55 | -0.23 | 0.96 | 0.16 |
| | | SS | 0.69 | 0.72 | 0.81 | -0.48 | -0.06 | 0.56 | 0.69 | 0.15 | 0.36 | -0.24 | -0.43 | -0.23 |
| | **All** | | **-0.35** | **-0.37** | **-0.14** | **-0.08** | **0.33** | **0.84** | **-0.11** | **-0.12** | **0.08** | **-0.16** | **0.54** | **0.19** |
| | All except | H2 | -0.32 | -0.34 | -0.15 | 0.00 | 0.35 | 0.91 | -0.14 | -0.16 | -0.02 | -0.13 | 0.56 | 0.42 |
| | All except class | 1 | 0.72 | 0.75 | 0.85 | -0.32 | 0.46 | 0.76 | 0.14 | 0.15 | 0.36 | -0.31 | -0.19 | -0.04 |
| Excluding class 1 | Fuel | C3H8 | 0.89 | 0.91 | 0.96 | -0.82 | 0.67 | 0.93 | 0.80 | 0.83 | 0.92 | -0.76 | 0.76 | 0.96 |
| | | CH4 | 0.79 | 0.80 | 0.91 | -0.74 | 0.72 | 0.96 | 0.70 | 0.71 | 0.86 | -0.67 | 0.78 | 0.98 |
| | | H2 | 0.22 | 0.23 | 0.35 | 0.02 | 0.82 | 0.89 | 0.22 | 0.23 | 0.35 | 0.02 | 0.82 | 0.89 |
| | | RP1 | 0.95 | 0.97 | 0.98 | -0.02 | 0.57 | 0.86 | 0.86 | 0.91 | 0.94 | 0.12 | 0.72 | 0.94 |
| | Material | Alu | 0.88 | 0.90 | 0.98 | -0.71 | -0.31 | 0.42 | 0.88 | 0.10 | 0.37 | -0.43 | -0.45 | -0.27 |
| | | CFRP | | -0.39 | -0.67 | -0.23 | 0.82 | 0.82 | | -0.06 | 0.42 | -0.41 | -0.53 | -0.54 |
| | | SS | 0.69 | 0.72 | 0.81 | -0.48 | -0.06 | 0.56 | 0.69 | 0.15 | 0.36 | -0.24 | -0.43 | -0.23 |

# Final LCA results – emissions/kg of payload deployed

- To account for sample size, a Student's t-test was performed with the following hypotheses:
  - Null hypothesis H0: the results are not correlated
  - Alternative hypothesis Ha: the results are correlated
- The table below filters the correlation coefficients to show those where the alternative hypothesis is accepted with a 95% (green) and 90% (yellow) confidence level

| | | | Excluding BC | | | | | | Including BC | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Nominal Payload | Achieved Payload | S1 Engine Number | TTWR | S1 Structural Fraction | S2 Structural Fraction | Nominal Payload | Achieved Payload | S1 Engine Number | TTWR | S1 Structural Fraction | S2 Structural Fraction |
| | Class | 1 | | | | | | | | | | | | |
| | | 3 | | | | | 0.84 | 0.85 | | | | | | |
| | | 4 | | 0.74 | 0.86 | | | | | | | | | |
| | Fuel | C3H8 | | | | | 0.70 | 0.89 | | | | | 0.73 | 0.91 |
| | | CH4 | | | | | 0.65 | 0.91 | | | | | 0.67 | 0.91 |
| | | H2 | | | | | 0.67 | 0.97 | | | | | 0.67 | 0.97 |
| | | RP1 | | | | | | 0.93 | | | | | | 0.95 |
| | Material | Alu | | | | | 0.75 | 0.89 | | | | | | |
| | | CFRP | -0.98 | -0.97 | | | | 0.88 | -0.98 | | | | 0.96 | |
| | | SS | 0.69 | 0.72 | 0.81 | | | | 0.69 | | | | | |
| | **All** | | | | | | | **0.84** | | | | | | |
| | All except | H2 | | | | | | 0.91 | | | | | | |
| | All except class | 1 | 0.72 | 0.75 | 0.85 | | | 0.76 | | | | | | |
| Excluding class 1 | Fuel | C3H8 | 0.89 | 0.91 | 0.96 | -0.82 | | 0.93 | 0.80 | 0.83 | 0.92 | -0.76 | 0.76 | 0.96 |
| | | CH4 | 0.79 | 0.80 | 0.91 | -0.74 | 0.72 | 0.96 | 0.70 | 0.71 | 0.86 | | 0.78 | 0.98 |
| | | H2 | | | | | 0.82 | 0.89 | | | | | 0.82 | 0.89 |
| | | RP1 | 0.95 | 0.97 | 0.98 | | | 0.86 | 0.86 | 0.91 | 0.94 | | 0.72 | 0.94 |
| | Material | Alu | 0.88 | 0.90 | 0.98 | -0.71 | | | 0.88 | | | | | |
| | | CFRP | | | | | 0.82 | 0.82 | | | | | | |
| | | SS | 0.69 | 0.72 | 0.81 | | | | 0.69 | | | | | |

# Conclusions

- Without considering black carbon and on a per mission basis, hydrogen seems to be better than both propane and RP-1, while methane has the greatest environmental impact due to the higher GWP of methane emissions.
- Including an assessment of the BC emissions it is clear that:
  - H2 has the lowest BC CO2e as it produces no black carbon impact (but is subject to an evaluation of radiative forcing of H2O in the upper atmosphere)
  - Propane and methane BC emissions increase their CO2e by approximately a factor of 100
  - RP1 has highest BC emissions (approximately 1000x higher than H2) and therefore highest total CO2e.
- **There is a 2 to 3 order of magnitude increase in CO2e for hydrocarbon fuels when including BC, i.e. Black carbon is very likely to dwarf everything else in terms of climate impact.** Propellants that emit a lot of black carbon, i.e. RP-1 in this study, are the worst. Even cleaner burning fuels such as propane and methane still perform worse than fuels that do not contain carbon such as hydrogen. **BC emissions are the dominate effect to consider when assessing the environmental impact of (hydrocarbon based) launch vehicles.**
- **There is no significant correlation between Life Cycle CO2e and payload capacity of a LV.** This is true across all vehicle configurations and when considering just architectures with common propellant types.
- Reducing LV structural mass fraction reduces Life Cycle CO2e per kg of payload
- Primary structural material has a relatively minor impact on life-cycle GWP100

# Future Work

- Analysis of impact of re-useability
- Evaluation of broader launch operations, e.g. transport to launch site
- Evaluation of GWP of H2O in upper atmosphere
- Actual emission measurements and/or up-to-date emission modelling are critical in order to revolve the high uncertainty around BC emissions for different propellants.
- Evaluation of different engine cycles on combustion emissions and black carbon production

# Thank You

The activities were carried out under a programme of and funded by the European Space Agency

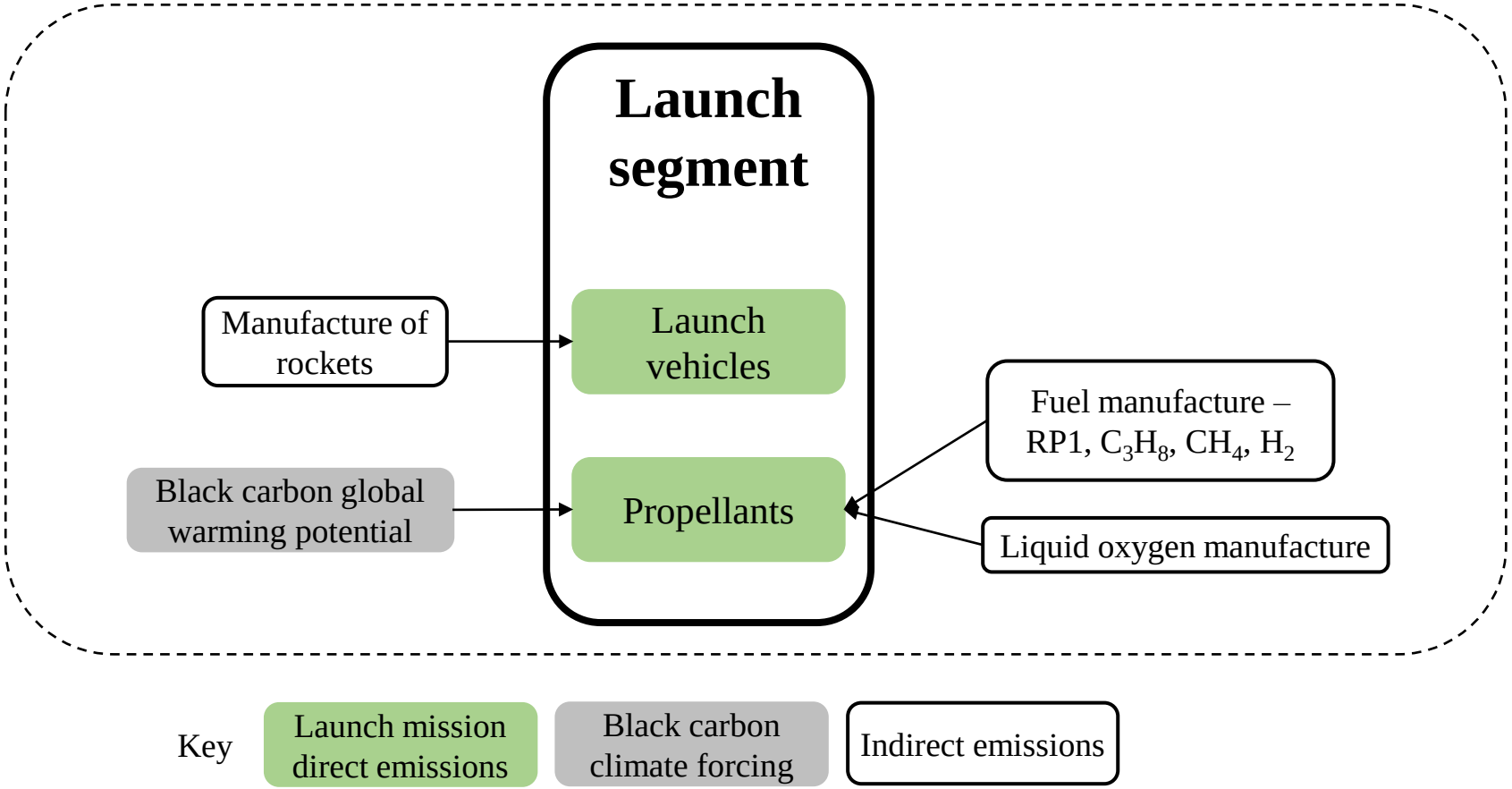
# Appendices

# Black Carbon: Emissions index

| Propellant | $EI_{BC}$ (g $kg^{-1}$)[a,b] | References/Rationale |
|---|---|---|
| Propane/LOX | 2 [1, 4] | • Assume ~90% reduction in soot emissions relative to RP1<br>• Supported by vehicle engine measurements. |
| $H_2$/LOX | 0 | Exhaust primarily water vapour |
| $CH_4$/LOX (Methalox) | 2 [1, 4] | • Data/research not available.<br>• Theoretically burns more cleanly than RP-1 and should produce less soot. |
| RP1/LOX (Keralox) | 20 [10, 40] | Ross & Sheaffer (2014) |
| RP-1/HTP (Kerosene/$H_2O_2$) (Class 1 only) | 12 [6, 24] | • Higher mixture ratio (8:1) relative to keralox (2.5:1), more complete combustion.<br>• ~40% reduction in soot emissions |
| $N_2O$/hydrocarbon (Hybrid)[c] | 40 [20, 80] | Ross & Sheaffer (2014) |
| Al/$NH_4ClO_4$ (Aluminium-Ammonia Percholorate)[c] | 4 [2, 8] | Ross & Sheaffer (2014) |

[a] grams emitted per kilogram of propellant (fuel + oxidizer) burned
[b] nominal [low, high]
[c] not considered in this study

# System boundary in this LCA assessment




LCA software used: SimaPro; background LCI database used: ESA LCA database (+Ecoinvent);
new foreground LCI datasets created: propellants, launch vehicles, launches