LCA of In-Space Propulsion Systems

Lily Blondel Canepari (UniPi), Lorenz Affentranger (ESA), Sara Morales Serrano (ESA), Enrico Tormena (ESA), Ferran Valencia Bel (ESA)

Clean Space Industrial Days 2023

10/10/2024

Agenda

Framework of the study

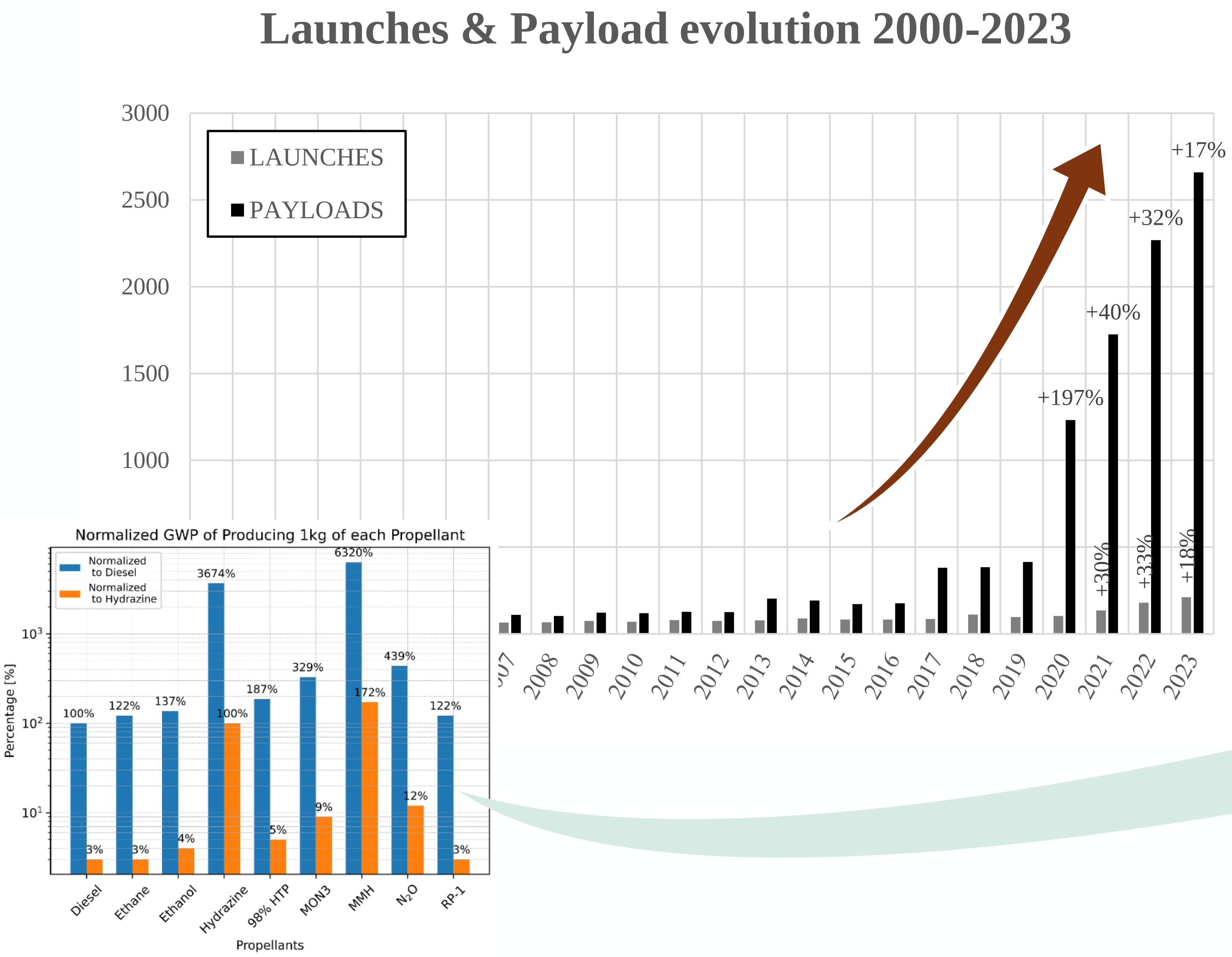
Single Score used

Environmental Impact of **Propellant Production** & **Loading**

Environmental Impact of **Dry Architecture vs. Propellant Loading**

Environmental Impact of **the Propulsion Systems**

Current Space Landscape: Exponential Increase of Activity



- ☐ Not only launches but also number of payloads has drastically increased over the last years (2019-2023):
  - ✓ **+118% launches**
  - ✓ **+540% payloads**
- ☐ Payload ratio has more than tripled since 2019 to reach 12.54% in 2023
  - ✓ More efficient propulsion systems
  - ✓ Miniaturization
- ☐ **Need to assess and mitigate the impact of Space Activities**
  - ➢ 1kg of Diesel → 0.8 kg of CO_2
  - ➢ 1kg of Hydrazine → 32 kg of CO_2
  - ➢ 1 kg of MMH → 55 kg of CO_2

General Framework: IN-ORBIT Propellants Selected

Transition to **Green Propellants**

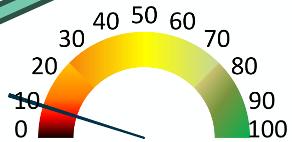
What is intended by Green ?

Legacy Option

Mixed Oxide of Nitrogen + Hydrazine Derivative (MON-3/MMH)

PROS	CONS
High performance	Extremely toxic
Hypergolic	Complex handling
Long Flight Heritage	Will be banned

Pressure-fed
Epump-fed



2 Main *Greener* Options for Liquid Bi-Propellants

Nitrous Oxide + High-vapor Pressure Fuel (N_2O/Ethane)

PROS	CONS
Low toxicity & propellant cost	Low performance
Long term storable	Low density → larger tanks
Simpler design (no extra pressurization)	High pressure storage

Self-pressurized

Hydrogen Peroxide + Low-vapor Pressure Fuel (98%HTP/Ethanol/RP-1)

PROS	CONS
Less toxic than Hydrazine	Need an ignition strategy
Higher density than hydrazine	Self-decomposition
Good performance	Material compatibility

Pressure-fed
Epump-fed

Hypothesis Made

Hypothesis made Propulsion-wise

- Considers **only the tank flight model**, not the development of the qualification route (significant assumption given that tanks computation is fine-tuned to the system and do not rely on existing tanks)
- Thickness of the liner is assumed constant and “average” of the real one, only to compute what input material is necessary. CFRP holds the whole pressure.
- Titanium tank manufacture route is taken as baseline
- Use of the fuelling room S5B is used for all propellants but with different equipment
- **Decontamination operation** includes only cleaning the line and not the part where lines are sent back to Europe for deep-cleaning
- **Passivation of components is missing for HTP**, together with a more stringent preparation/decontamination procedure

Hypothesis made LCA-wise

- data from the ESA database v1.2.0f, Ecoinvent v3.9.1 and analysed with SimaPro v9.4.0.3.
- Cut-off allocation is used.
- **Infrastructures are excluded**.
- Long-Term Emissions are included.
- Component losses from production to gate is estimated to 10%, however, this does not represent the amount of propellant targeted for decontamination and waste treatment which is instead considered constant after each use of the pipes.
- After fuelling operations, unused propellant quantities are transported back to the contractor and stored for another use. However, since the spare propellant is not always used for another mission, the production of unused propellant quantities was included into the system boundaries.

Agenda

Framework of the study

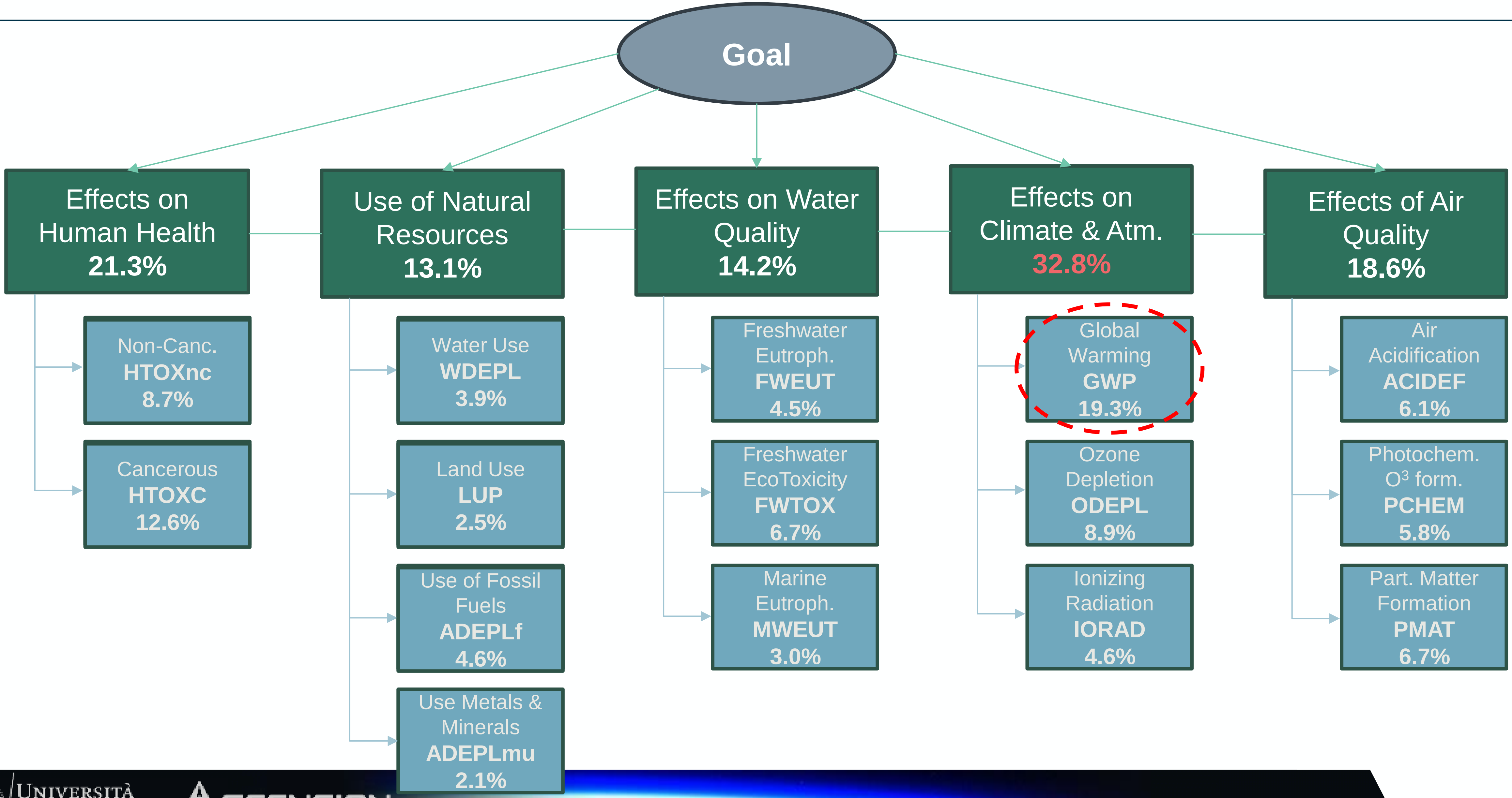
Single Score used

Environmental Impact of **Propellant Production** & **Loading**

Environmental Impact of **Dry Architecture vs. Propellant Loading**

Environmental Impact of **the Propulsion Systems**

AHP-derived Weights for the Midpoint Indicators



Goal

Effects on Human Health
21.3%

- Non-Canc. **HTOXnc** **8.7%**
- Cancerous **HTOXC** **12.6%**

Use of Natural Resources
13.1%

- Water Use **WDEPL** **3.9%**
- Land Use **LUP** **2.5%**
- Use of Fossil Fuels **ADEPLf** **4.6%**
- Use Metals & Minerals **ADEPLmu** **2.1%**

Effects on Water Quality
14.2%

- Freshwater Eutroph. **FWEUT** **4.5%**
- Freshwater EcoToxicity **FWTOX** **6.7%**
- Marine Eutroph. **MWEUT** **3.0%**

Effects on Climate & Atm.
32.8%

- Global Warming **GWP** **19.3%**
- Ozone Depletion **ODEPL** **8.9%**
- Ionizing Radiation **IORAD** **4.6%**

Effects of Air Quality
18.6%

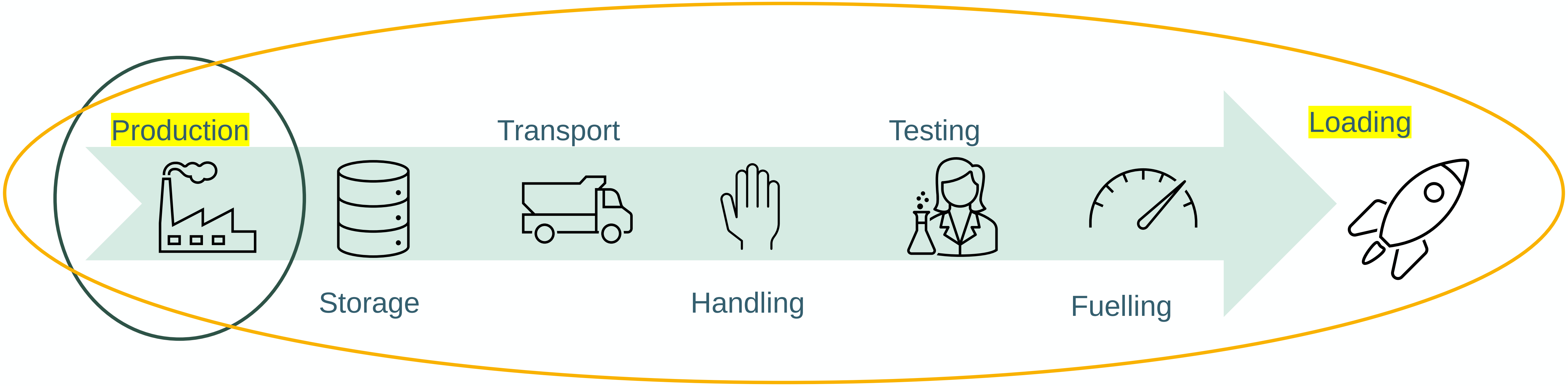
- Air Acidification **ACIDEF** **6.1%**
- Photochem. O^3 form. **PCHEM** **5.8%**
- Part. Matter Formation **PMAT** **6.7%**

Comparison with the Weights used by PEF

Agenda

- **Framework** of the study
- **Single Score LCA** used
- Environmental Impact of **Propellant Production** & **Loading**
- Environmental Impact of **Dry Architecture vs. Propellant Loading**
- Environmental Impact of **the Propulsion Systems**

The Ground Life Phases: from Production to Gate



Production

Storage

Transport

Handling

Testing

Fuelling

Loading

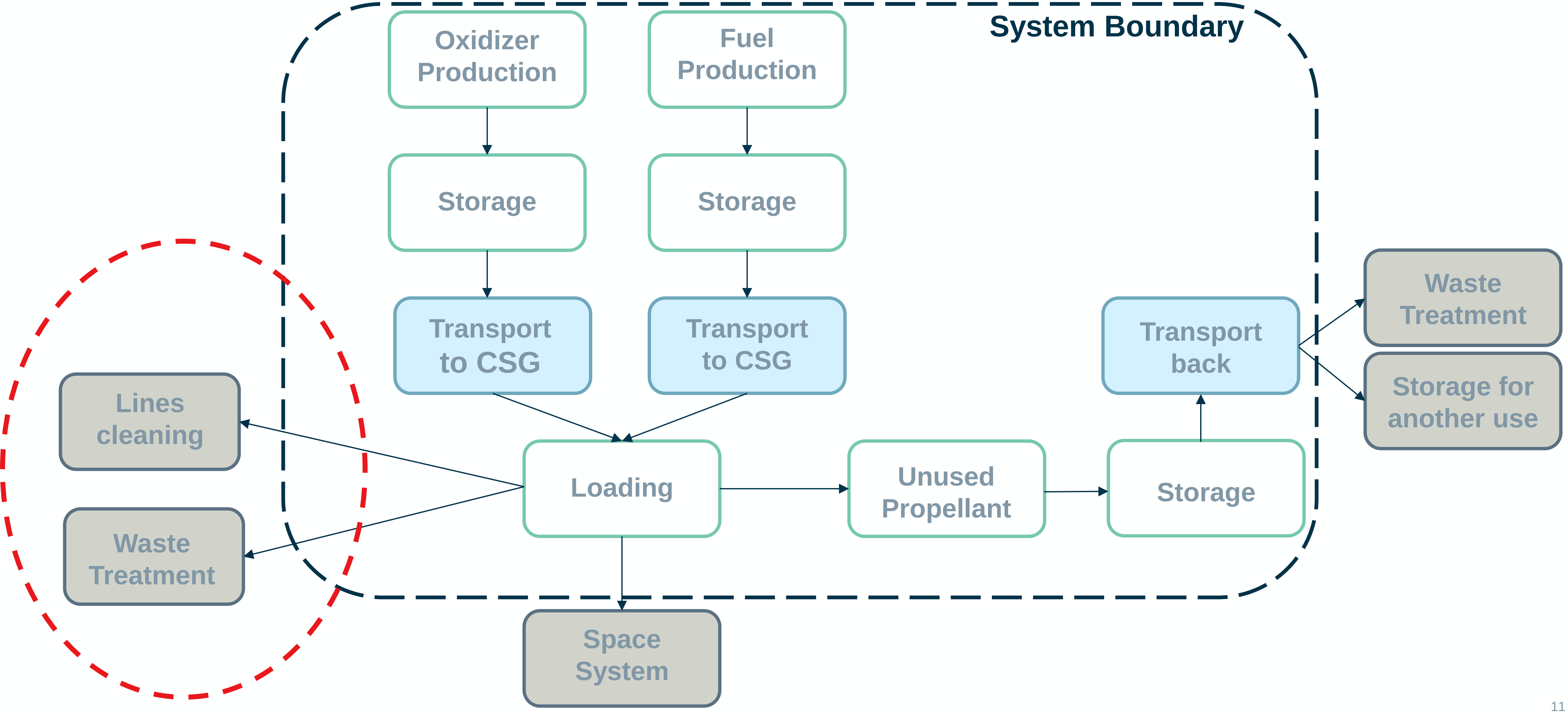
Two types of data:

- The one assessing the impact of **production phase** only
- The one assessing the impact of **cradle-to-gate** life cycle, i.e. including all the ground life phases until loading in the space system

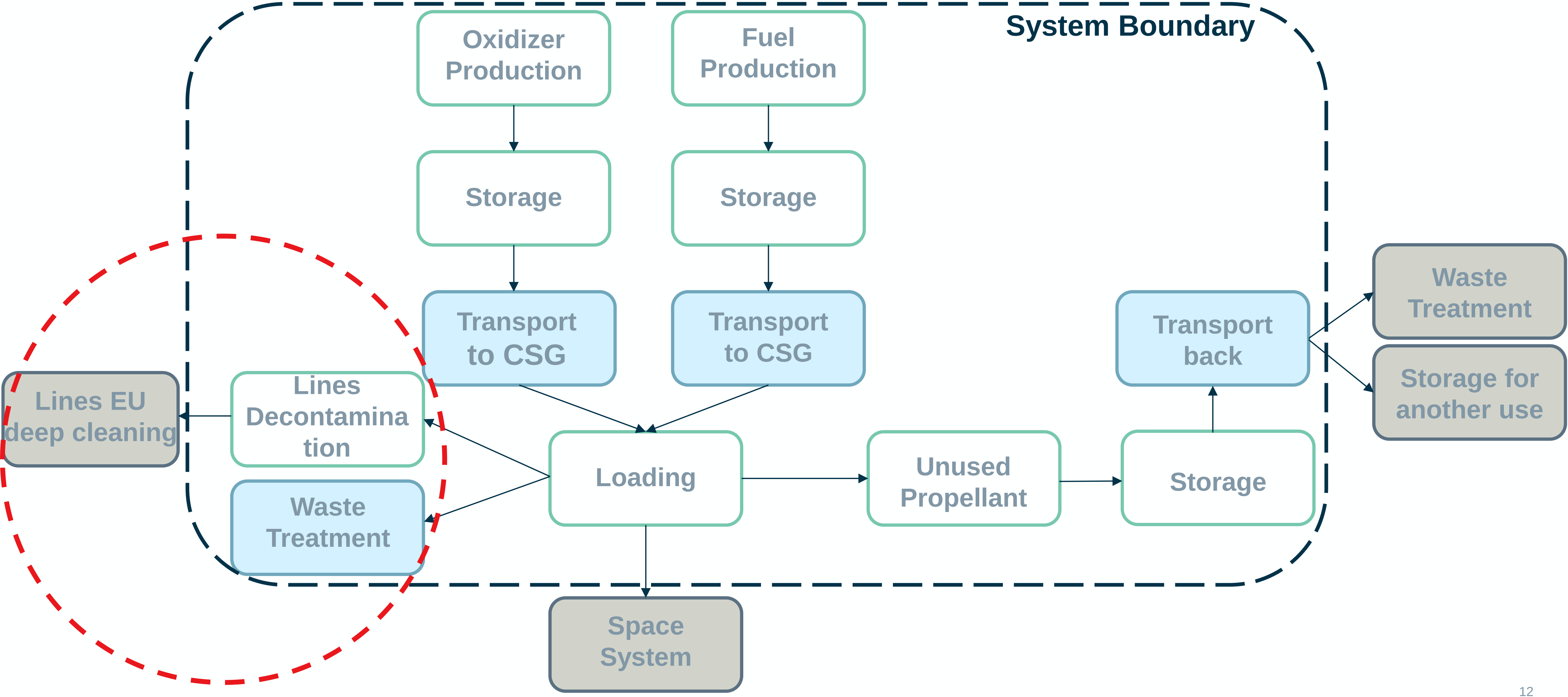
Phase Contribution:

Without Decontamination, the propellant **production is by far the most impactful (~90%)** of the life phases for MON-3 and HTP while the losses between production and fuelling are the most impactful for N_2O (high-GWP).

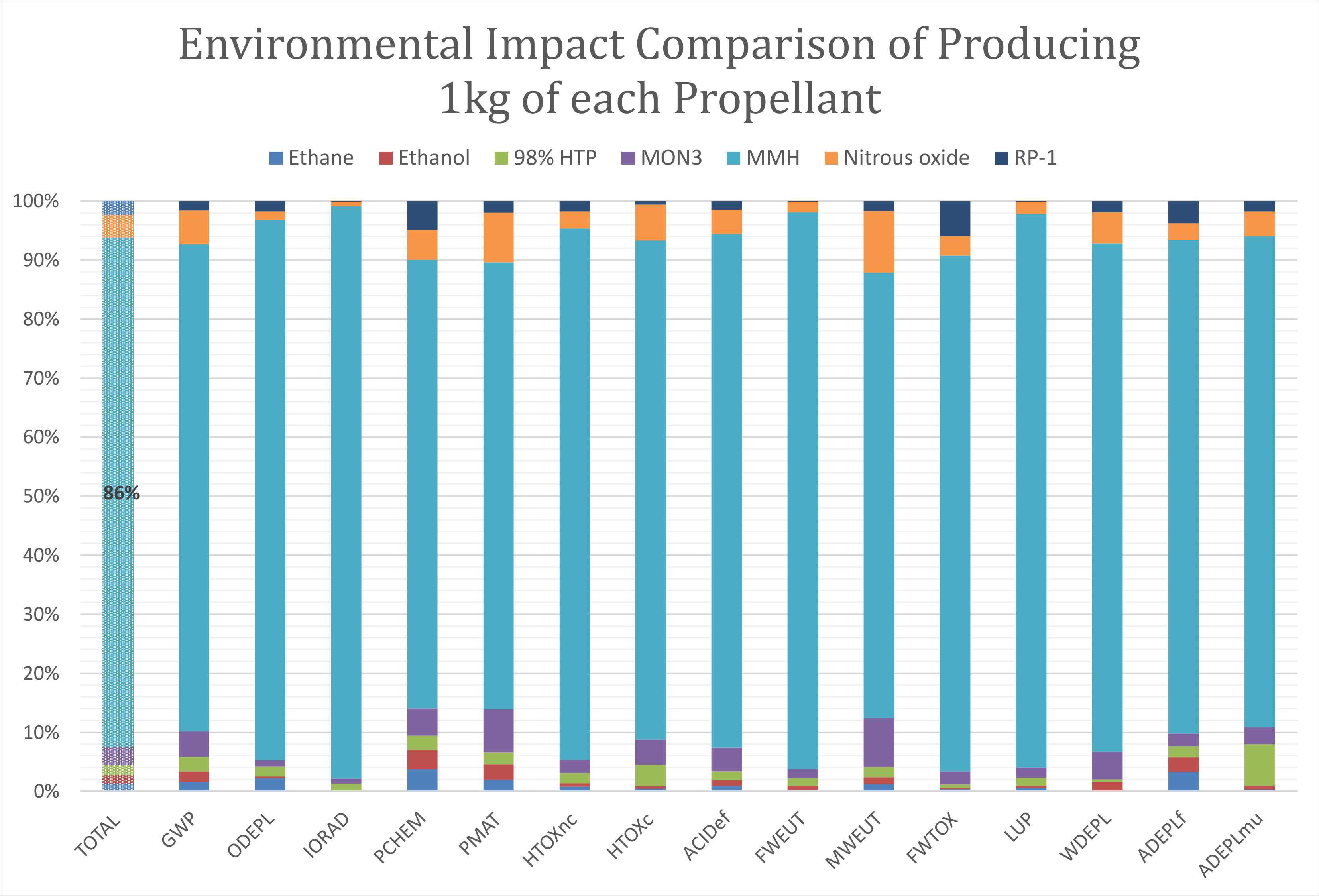
System Boundary of Propellant Loading alone – 1 kg



System Boundary of Propellant Loading for the Mission

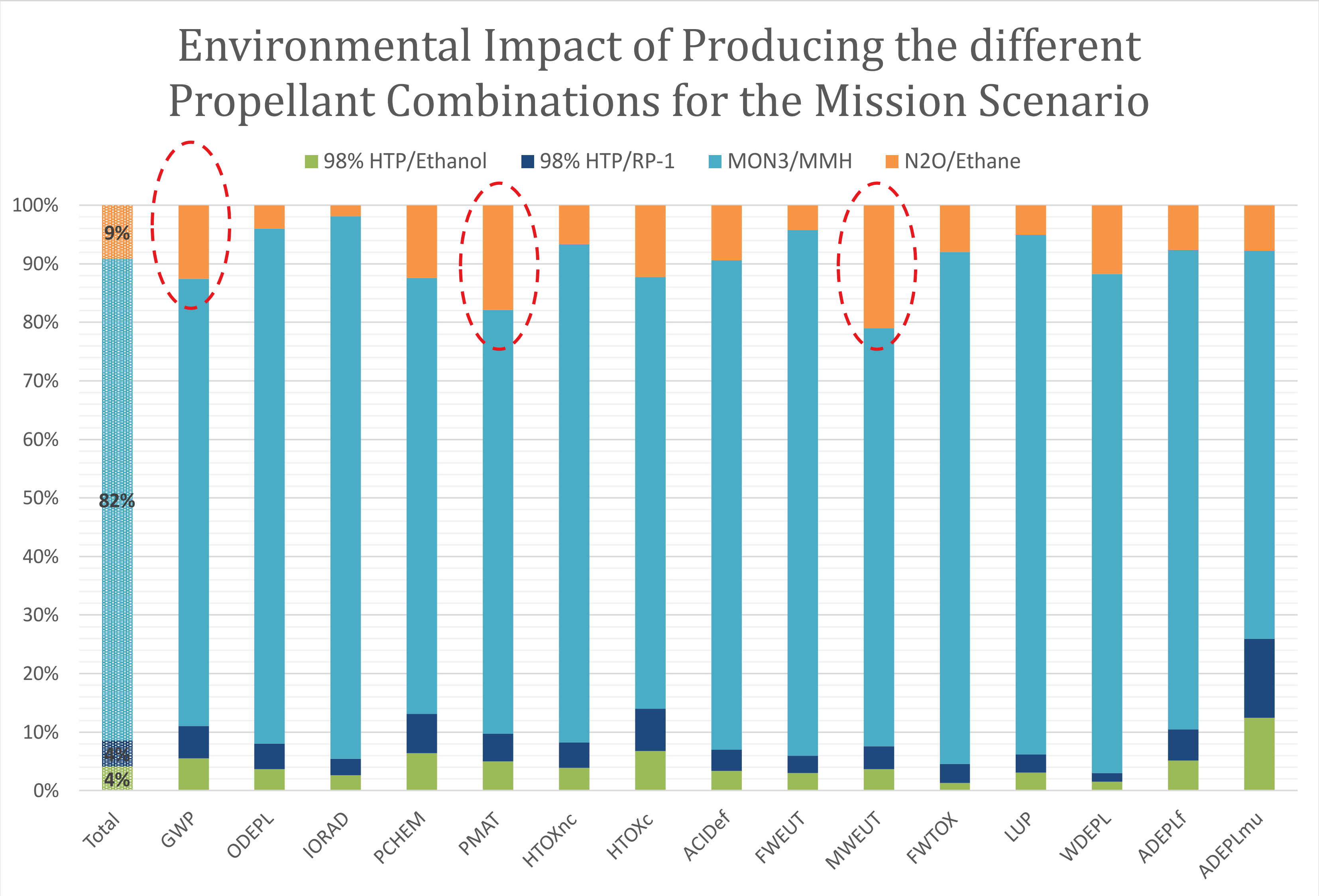


LCA OUTPUT – Production of 1 kg of Propellants



- ❑ The production of 1 kg of MMH has the highest environmental impact across all categories, attributed primarily to:
  - ○ **High energy demands** required for its production
  - ○ Its specialized, **small-scale manufacture** for space applications

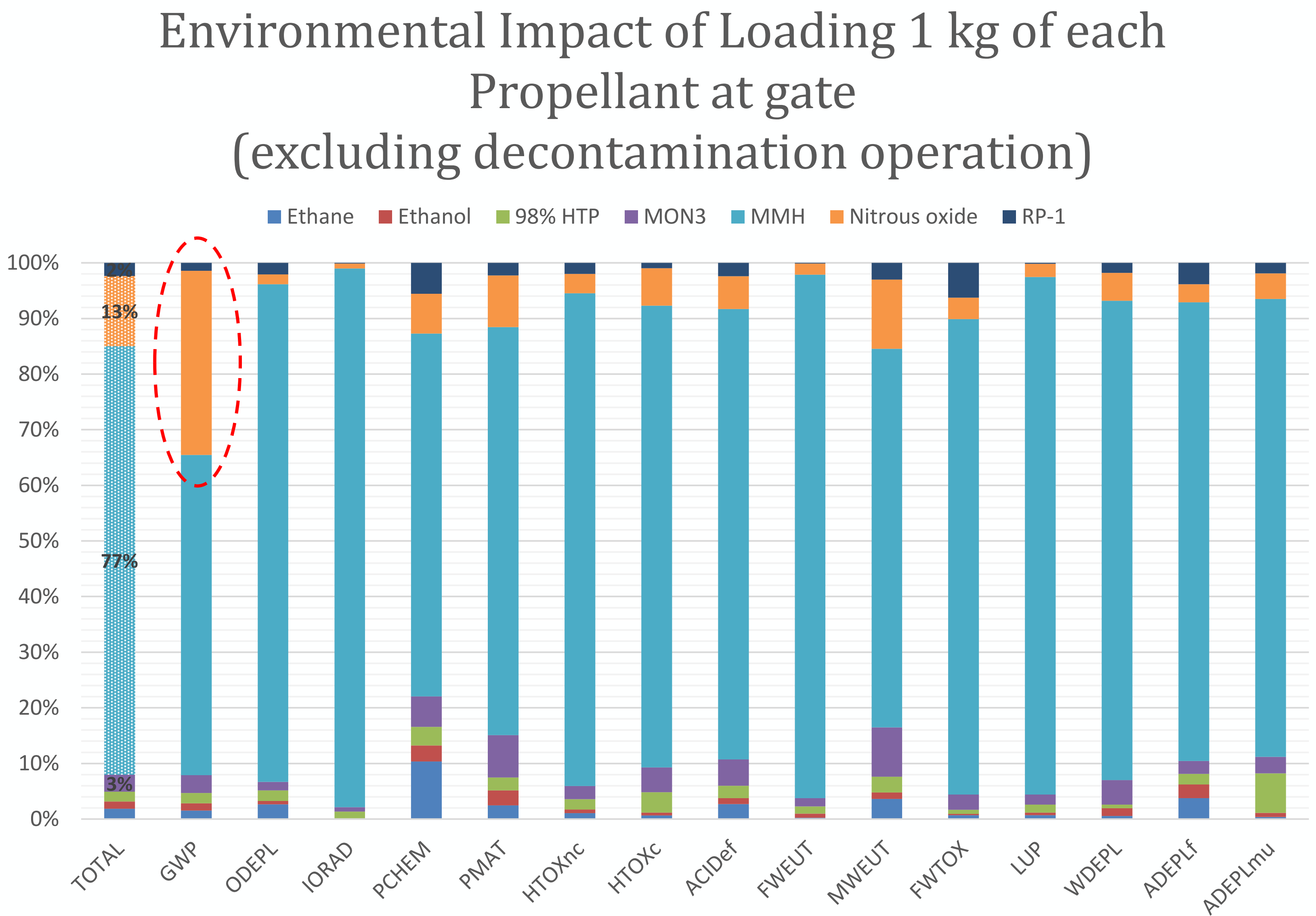
OUTPUT – Production of the Propellants for the mission



	I_{sp} [s]	Densities [kg.m^{-3}]	Ideal O/F
MON-3/MMH	325	1440/875	1.65
98% HTP/RP-1	305	1437/800	7.5
98% HTP/Ethanol	300	1437/789	4.5
N_2O/Ethane	295	785/340	7.0

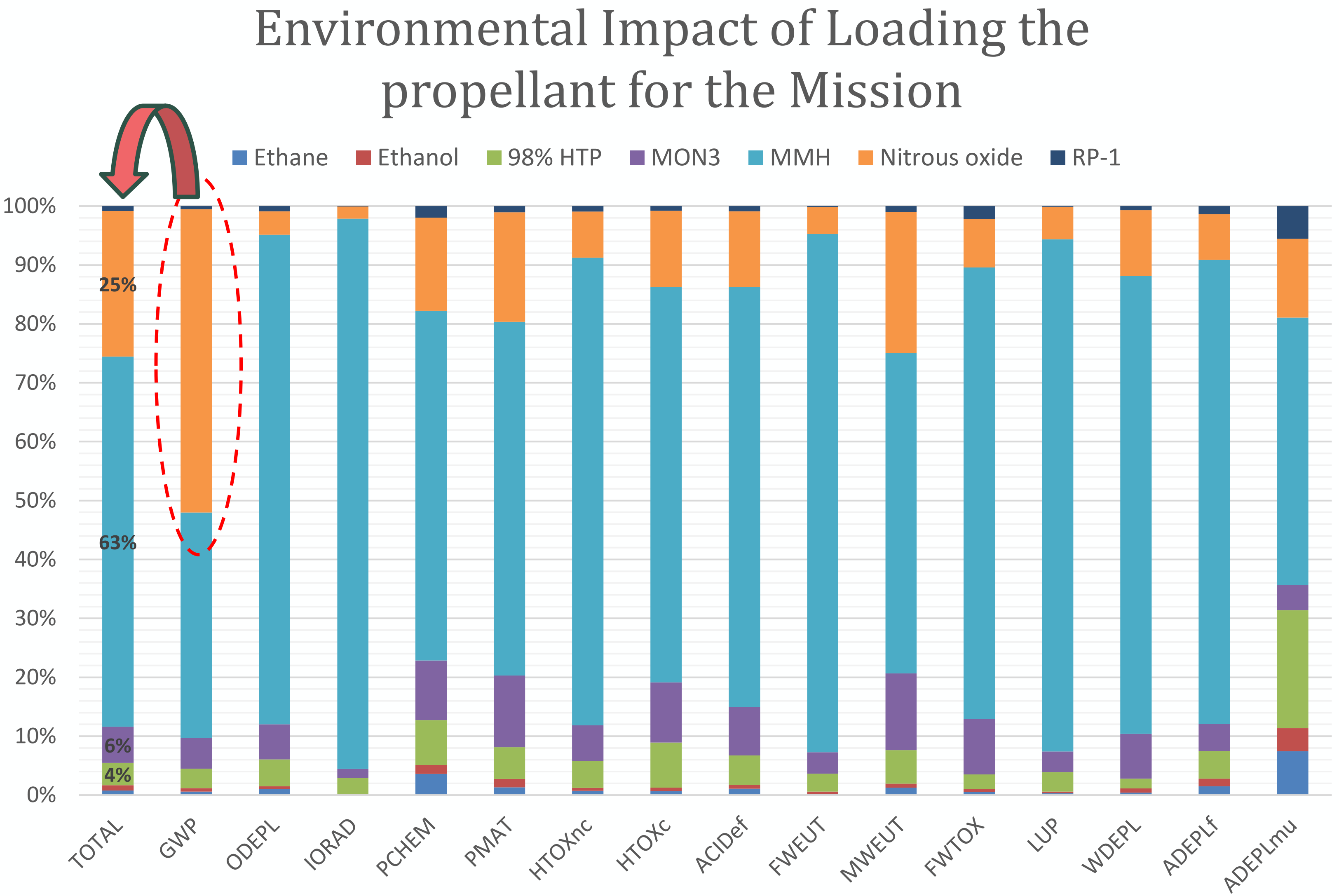
- High O/F ratio of the “greener” option makes the total weight of the propellant combination led by the impact of the oxidizer
- This impact is “higher” for N_2O in air emissions and water quality indicators due to its production process relying on ammonia oxidation:
    - Emission of ammonium ions in water
    - Emission of NO species in air

OUTPUT – Loading of 1kg of Propellants


Environmental Impact of Loading 1 kg of each Propellant at gate
(excluding decontamination operation)

- Loading shifts the contribution
- MON3/MMH still the most impacting
- But Nitrous Oxide shows a non-negligeable overall impact due to its contribution to GWP (due to losses in storage → GWP gas emissions)

OUTPUT – Loading of the Propellants for the mission



	Δv	Wet Mass	Thrust
GEO Delivery	~ 2300 m/s	3200 kg	2 kN

- ❑ Decontamination Operations are included
- ❑ MON3/MMH still the most contributing
- ❑ But Nitrous Oxide shows a high overall impact due to its contribution to GWP
- ❑ Self-pressurized combination is the second worse for propellant loading

Agenda

Framework of the study

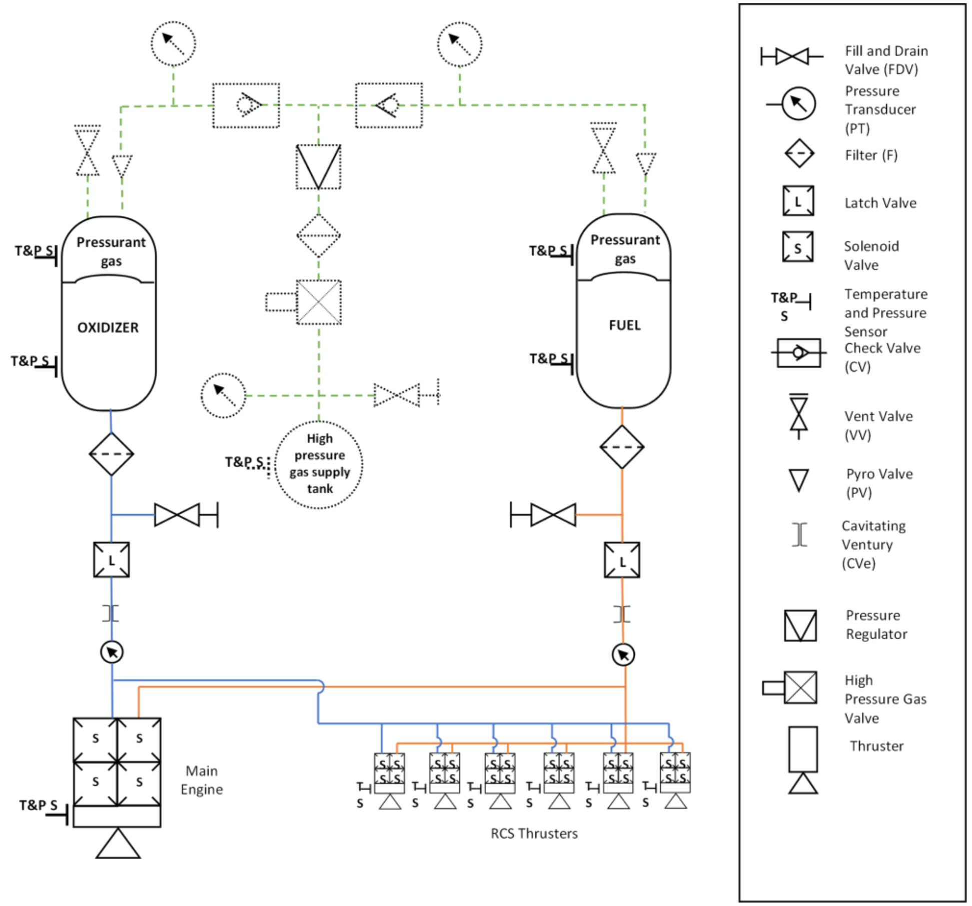
Single Score LCA used

Environmental Impact of **Propellant Production** & **Loading**

Environmental Impact of **Dry Architecture vs. Propellant Loading**

Environmental Impact of **the Propulsion Systems**

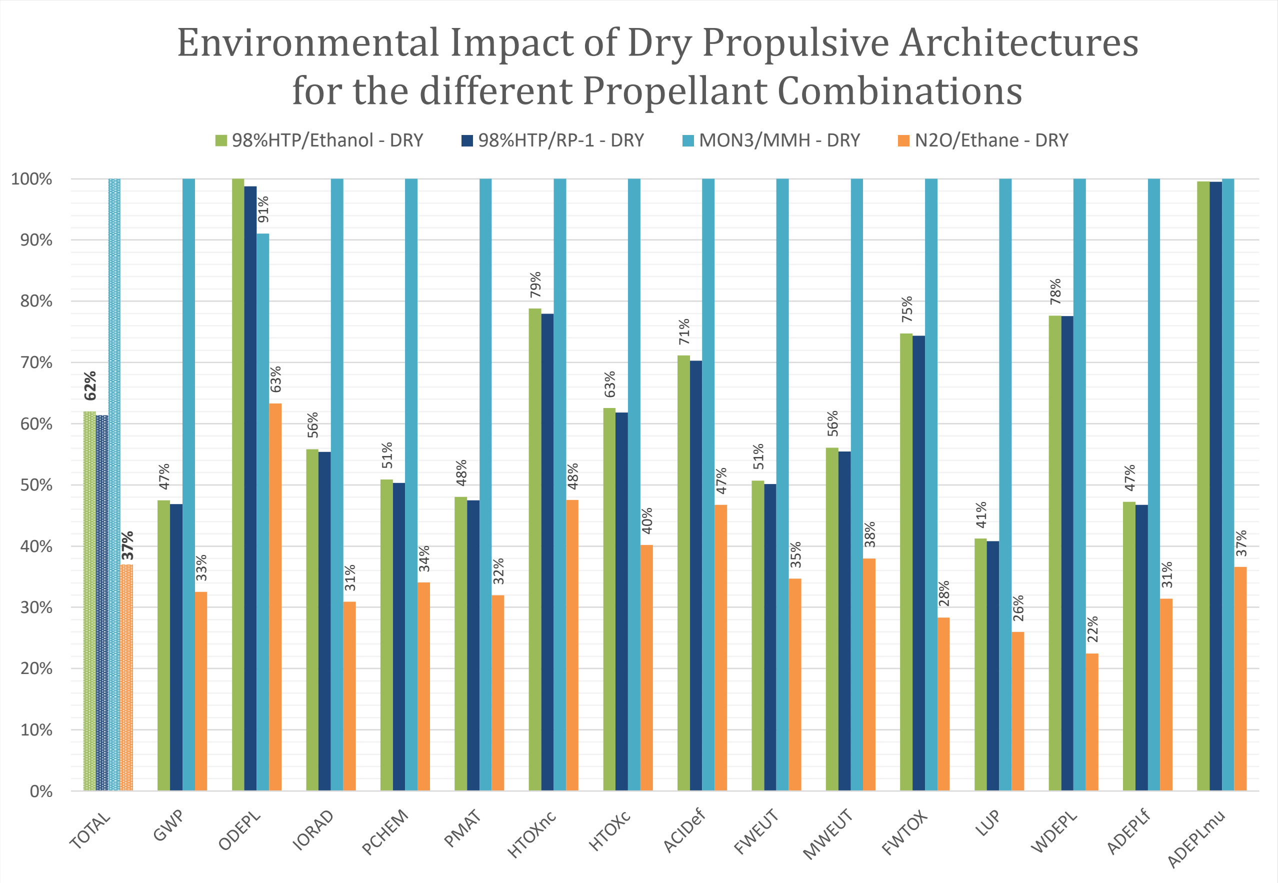
Baseline architecture tuned to the Propellants



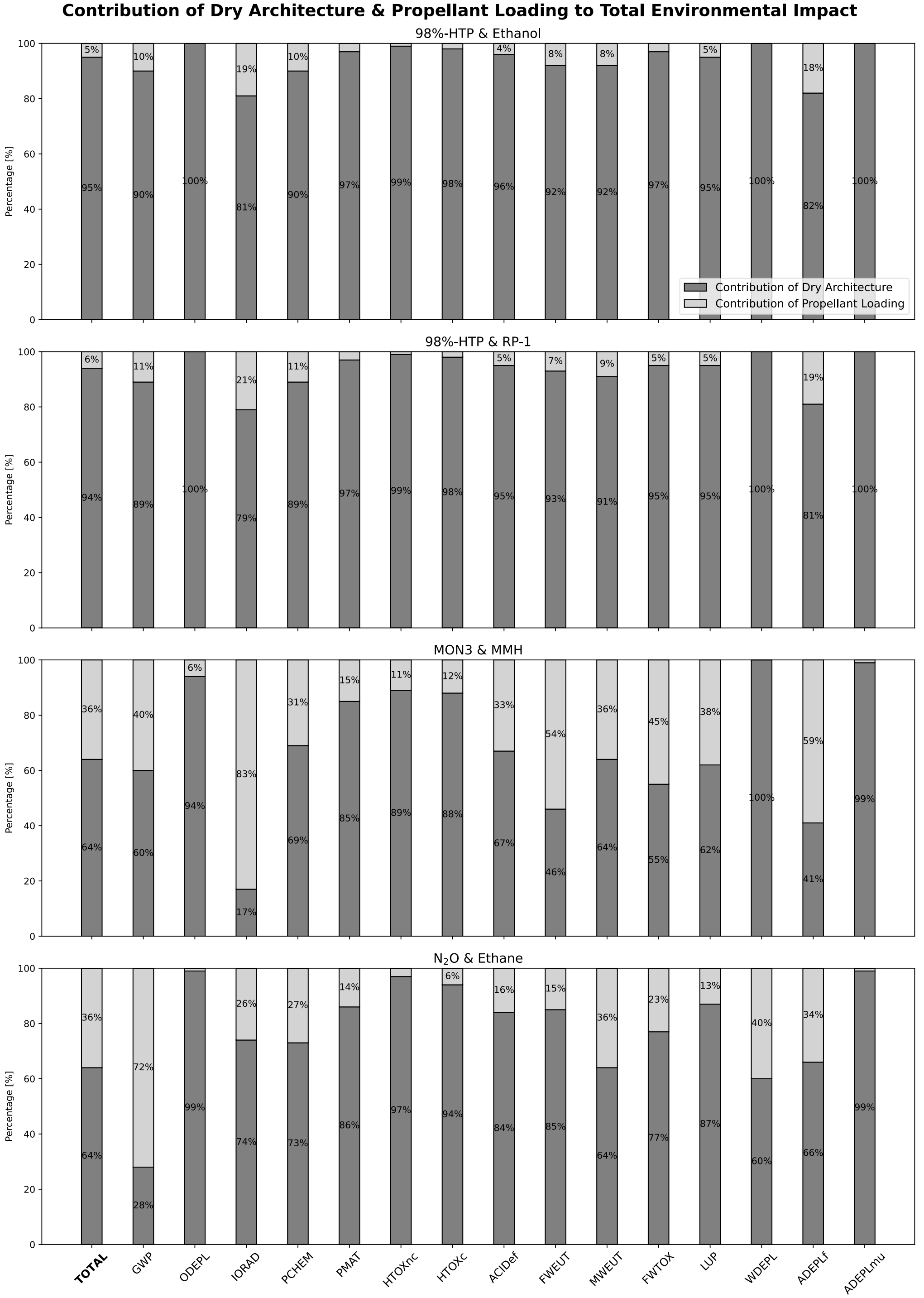
	MON-3 & MMH	98%HTP & Ethanol or RP-1	N_2O & Ethane
Oxidizer Tank	1 Cyl. TiAl6V4	1 Cyl. AA5254 with CFRP Overwrap	1 Cyl. C. Fiber with TiAl6V4 liner
Fuel Tank	1 Cyl. TiAl6V4	1 Cyl. AA6060 with CFRP Overwrap	1 Cyl. C. Fiber with TiAl6V4 liner
Pressurizing He Vessel	2	2	None
Filters	4	4	2
Pyro Valves	2	2	None
Vent valves	None	2	2
Fill & Drain Valves	4	4	2
Latch Valves	2	2	2
Cavitating Venturi	2	2	2
Pressure Transducers	6	6	2
Pressure Regulator	2	2	None
High P. Gas Valve	2	2	None
T. & P. Sensors	6	6	4
Solenoid Valves	20	20	20
Main Thrusters	5	5	5
Tubing	Titanium	Aluminium	Titanium

- ☐ Each propellant combination has a specific architecture, fine-tuned to its properties (components, material). The self-pressurized one gets rid of all the dashed line (i.e. all the pressurization elements).
- ☐ The architecture is sized to the GEO mission scenario

Impact of the Architecture vs Propellant Loading



Environmental Impact of Dry Propulsive Architectures for the different Propellant Combinations



Contribution of Dry Architecture & Propellant Loading to Total Environmental Impact

- ❑ In pressurized HTP-systems, the manufacturing of the dry architecture contributes to approximately **95%** of the total environmental impact
- ❑ In contrast to **64%** for both the MON3/MMH and self-pressurized systems
- ❑ Architecture-wise, the self-pressurized is the most environmentally-friendly

Agenda

Framework of the study

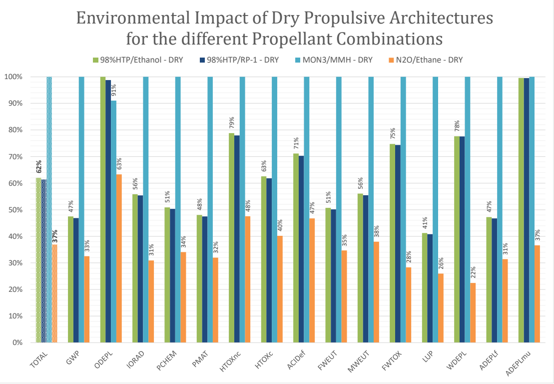
Single Score LCA used

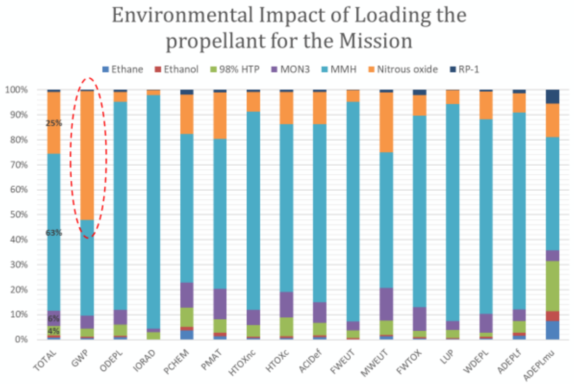
Environmental Impact of **Propellant Production** & **Loading**

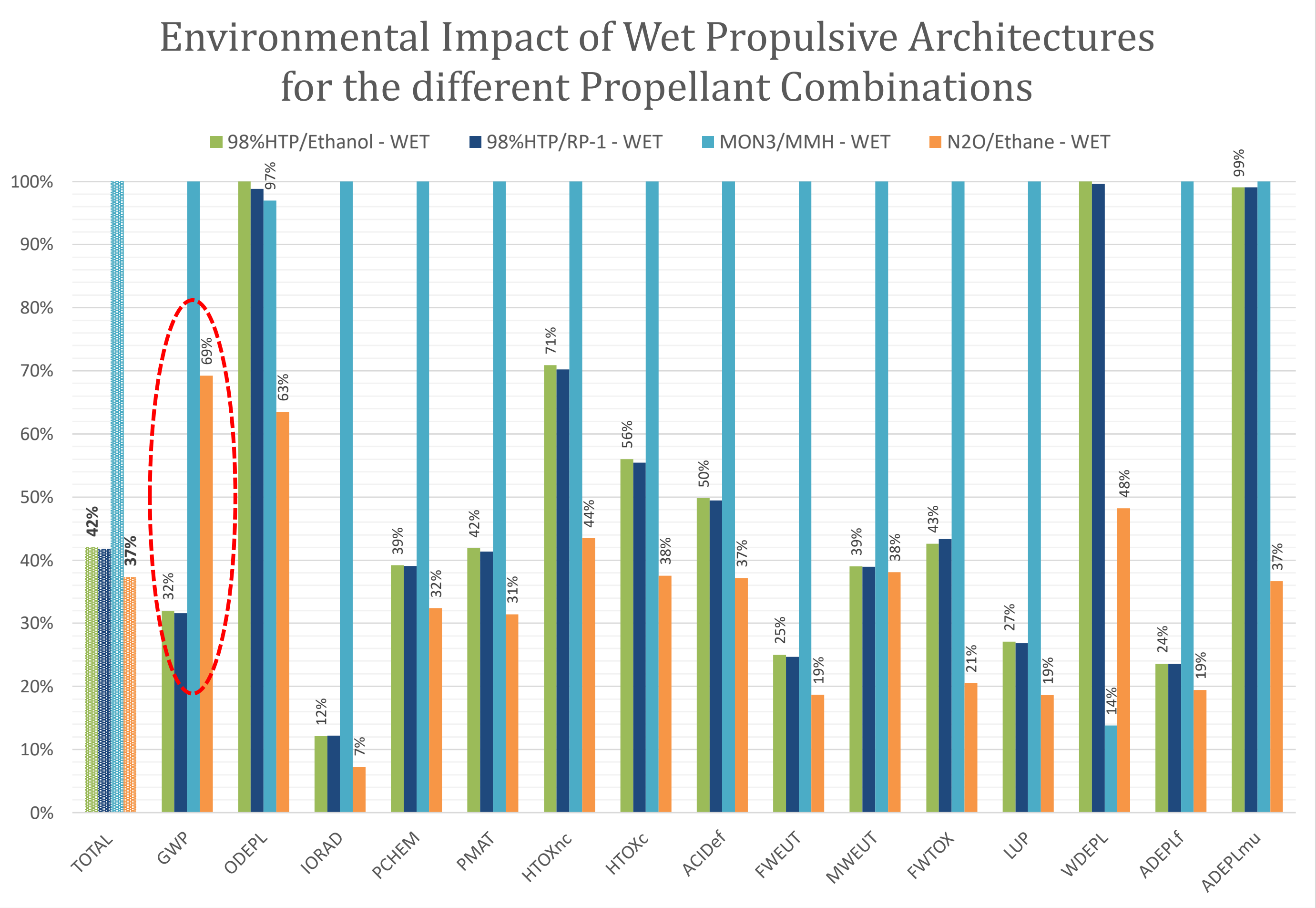
Environmental Impact of **Dry Architecture vs. Propellant Loading**

Environmental Impact of **the Propulsion Systems**

Impact of the whole propulsion system

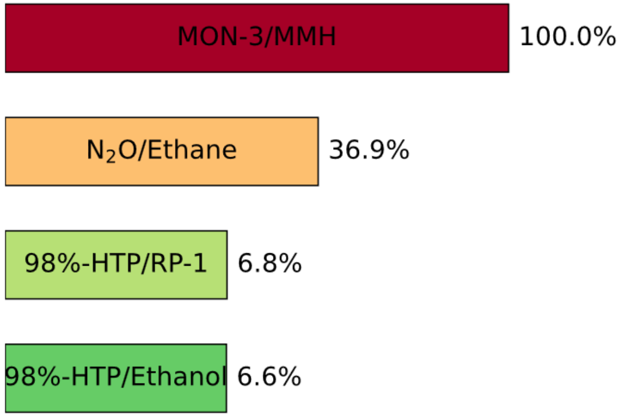

Environmental Impact of Dry Propulsive Architectures for the different Propellant Combinations


Environmental Impact of Loading the propellant for the Mission

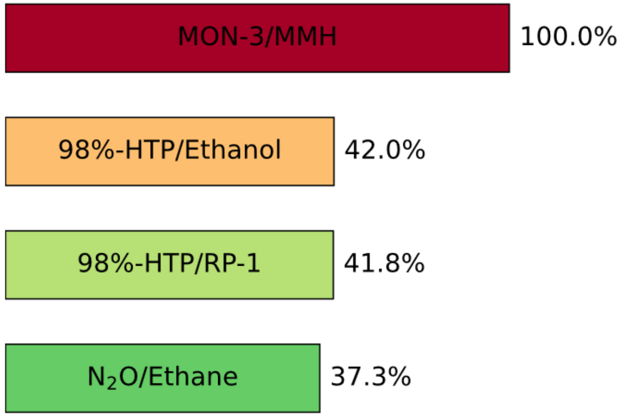

Environmental Impact of Wet Propulsive Architectures for the different Propellant Combinations

- ☐ Considering the whole system, the self-pressurized option is the most environmentally-friendly in terms of total impact
- ☐ But it would score low looking only at GWP → danger of reducing environmental impact to CO_2 emissions

Comparison of System-wide Propulsive Options LCA



Relative Impact of Propellant Loading for GEO Mission
(incl. propulsive performance)

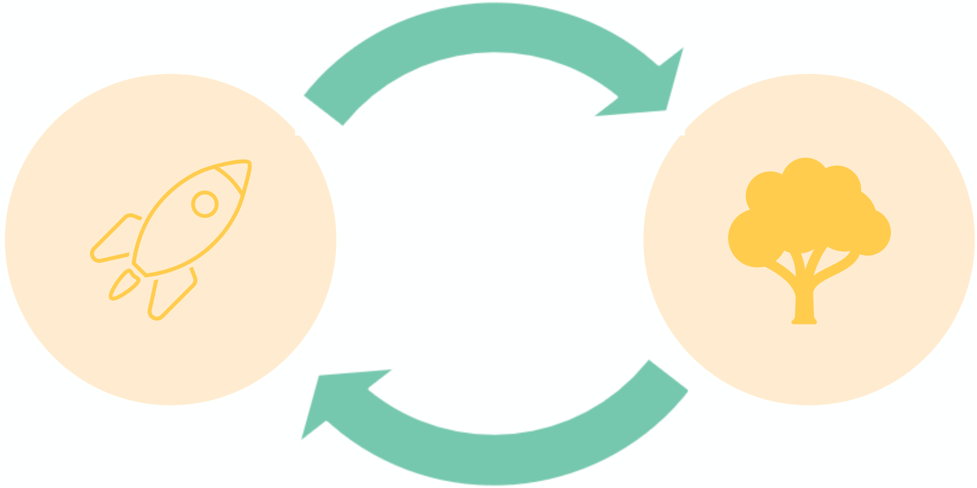


Relative Impact of Propellant Loading + Dry Propulsion System for GEO Mission

- Considering only **propellant impacts**, **HTP-based systems are the greenest** (due to the GWP impact of N_2O)
- Considering the **whole system**, the **self-pressurized option** stands out as the **greenest option**
- *Both HTP-based and N_2O-based option* ***CAN*** *be labelled as* ***green***

Conclusion & Ways Forward

- ✓ **LCA should be performed** to get a full picture of the environmental impacts, uncovering hotspots, avoiding burden shifting and aiming for improvements (i.e. **eco-design**)
- ✓ *Greener* propellants **does not mean only "less toxic"**
- ✓ Out of the propellants studied, single score LCA indicates the self-pressurized combination **N_2O/Ethane** as the **most eco-friendly** combination but the second worst one in terms of GWP
- ✓ Greener propellants is good but **most of the impact is hold by the architecture** → emphasis on green MAIT
- ✓ Multiple use (**reusable & refuelling**) would be beneficial
- ✓ While is it currently difficult due to the lack of data, LCA should be applied **as early as possible** in the mission definition phases when the design is still flexible



DESIGN CHOICE

ENVIRONMENTAL IMPACT

Recommendation for future activity:

- ☐ Broader data collection survey
- ☐ New studies to include new propellants and manufacturing processes → more accurate scenarios
- ☐ Importance of Green MAIT

Questions?

Reach out to **Lily Blondel Canepari**: lily.blondel@ing.unipi.it