Comparative life cycle sustainability assessment of novel monopropellant systems

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Contents

1.
Introduction

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Novel monopropellants

- Three-decade-long research effort to find alternatives to hydrazine which meet or exceed its performance with improved ease of use
- Four main groups:
  - Hydrogen peroxide-based
  - Nitrous oxide-based
  - Energetic Ionic Liquids (EILs)
  - Water electrolysis
- Flight heritage with all four, most promisingly with EILs LMP-103S and ASCENT (AF-M315E)

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Dinardi and Persson 2012

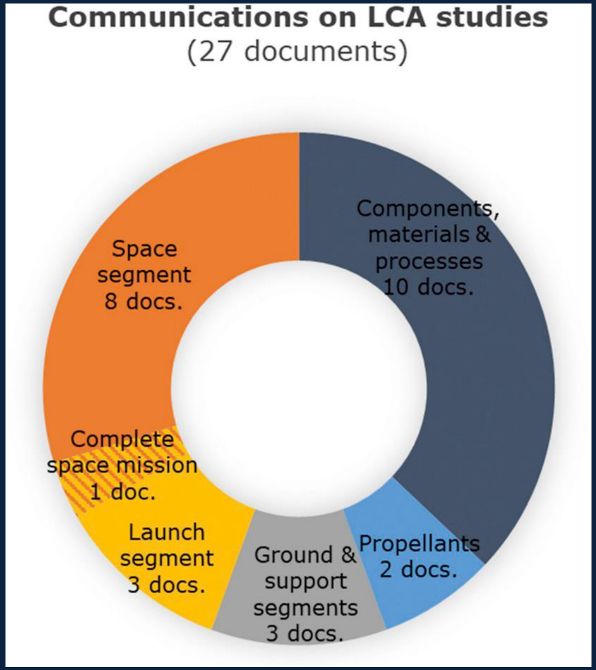

Masse et al. 2016


Dinardi et al. 2017

LC(S)A of monopropellants

- LCA methodology provides a useful tool to move beyond the focus on propellant toxicity
- LCSA adds social and economic impacts to the traditional environmental LCA: especially fitting for novel monopropellant context
- Few prior research efforts on life cycle sustainability of monopropellant systems

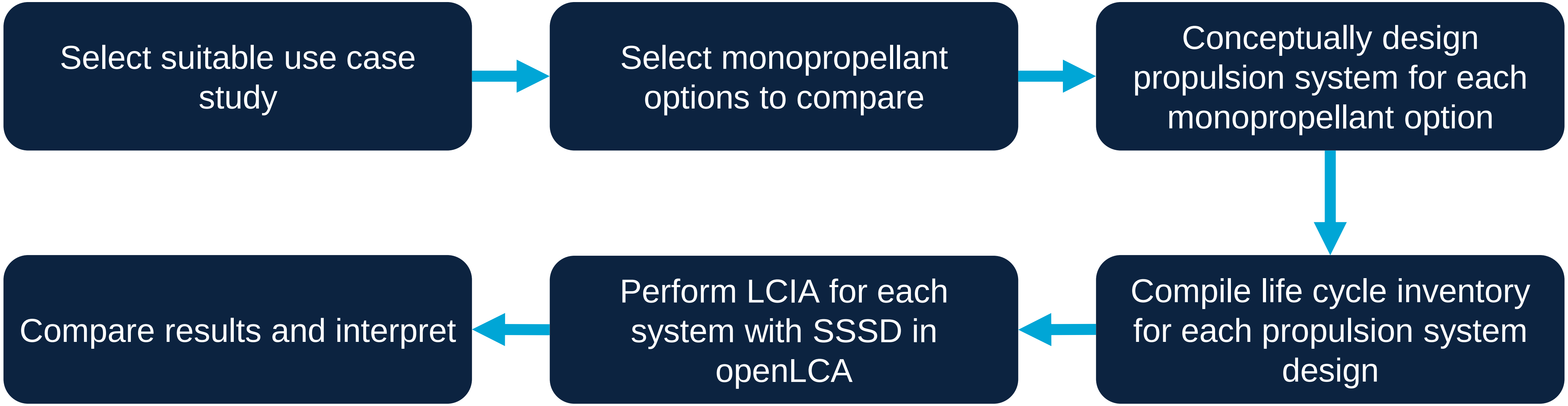
Wall Street Journal 2022



Maury et al. 2020

How does the choice of propellant impact the environmental, social and economic life cycle sustainability of a representative monopropellant system?

Research structure



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4.
Case Study Design

Considered use cases

1. Main propulsion system for a 6U CubeSat in an Earth Observation (EO) or Internet of Things (IoT) constellation in LEO. (Kepler, Spire)
2. Main propulsion system for a 12U CubeSat used for a deep space exploration mission. (Lumio)
3. Main propulsion system for a minisatellite in an EO constellation in LEO. (SkySat)
4. Attitude control system for a navigational satellite in a MEO constellation. (Galileo)
5. Roll and attitude control system for a medium-lift launch vehicle. (Vega-C)

Key propulsion system requirements

- The propulsion system shall have a total dry mass of less than 11 kg.
- The propulsion system shall have a total volume of less than 0.04 m^3.
- The propulsion system shall provide a total ΔV of 153.53 m/s.
- The propulsion system shall fulfil all its requirements over the mission lifetime of 10 years.
- The propulsion system shall be capable of providing impulse changes in 3 degrees of freedom.

Monopropellant trade-off

Criteria:

- Performance (Isp)
- Data availability
- System complexity
- Propellant density
- Safety
- Storability

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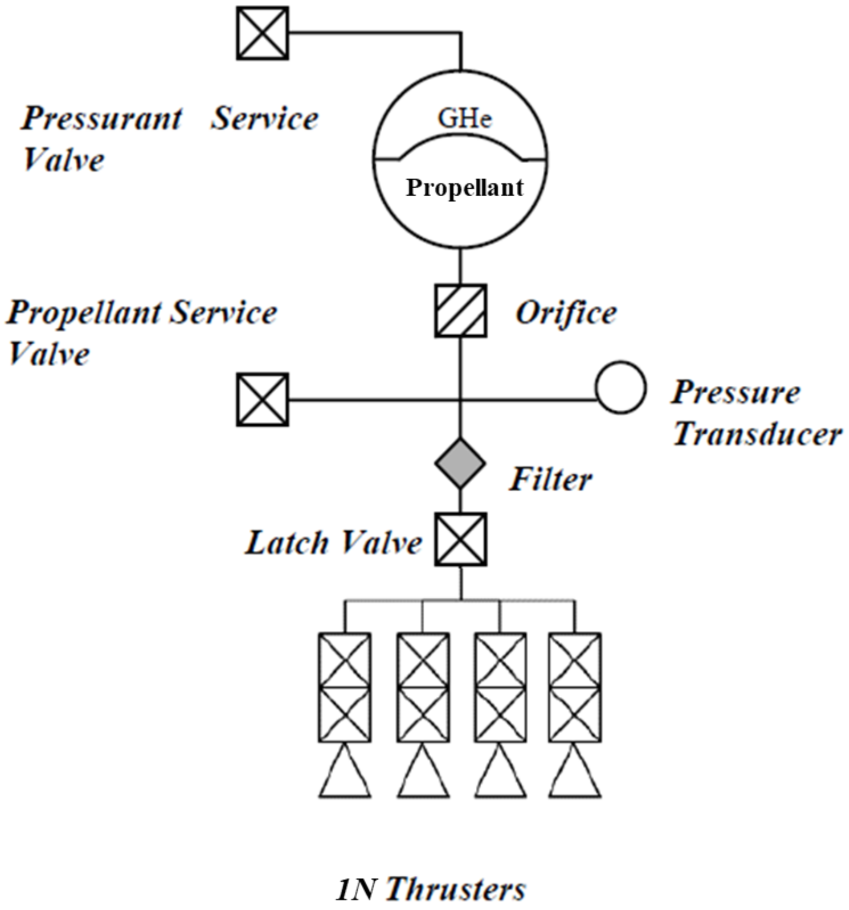
Propellant group	Propellant	Trade-off score %
Baseline	Hydrazine	80
HP-based	98% Hydrogen peroxide	70
HP-based	90% Hydrogen peroxide/ethanol blend	60
NO-based	Nitrous oxide	46
NO-based	HyNOx	57
NO-based	NOFBX	49
ADN-based	LMP-103S	78
ADN-based	FLP-106	69
HAN-based	ASCENT	80
HAN-based	SHP163	73
HAN-based	GEM (Green Electric Monopropellant)	63
Water electrolysis	Water	77

Common system architecture and design constraints

- Based on heritage (novel) monopropellant systems: Myriade, PRISMA, GPIM, SkySat
- Satellite dry mass of 150 kg
- Pressure-fed 4:1 blowdown system
- Four 1N thrusters



Propulsion system designs

- Same valves, filter, pressure transducer and tubing for all cases
- Titanium tank for all except 98% HP, for which Al 5254 is used
- Tank sizing proportional to propellant load
- Thrusters selected specifically for propellant

Propellant	Hydrazine	ASCENT	LMP-103S	98% Hydrogen Peroxide
Theoretical Isp [s]	239	266	255	190
Propellant mass [kg]	12.28	10.99	11.48	16.61
Tank mass [kg]	2.48	1.79	2.07	3.15
Total dry mass [kg]	5.97	5.14	5.52	6.89
Total wet mass [kg]	18.27	16.14	17.02	23.52
Difference w.r.t. baseline [%]	0	-11.7	-6.8	+28.7

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LCSA Methodology

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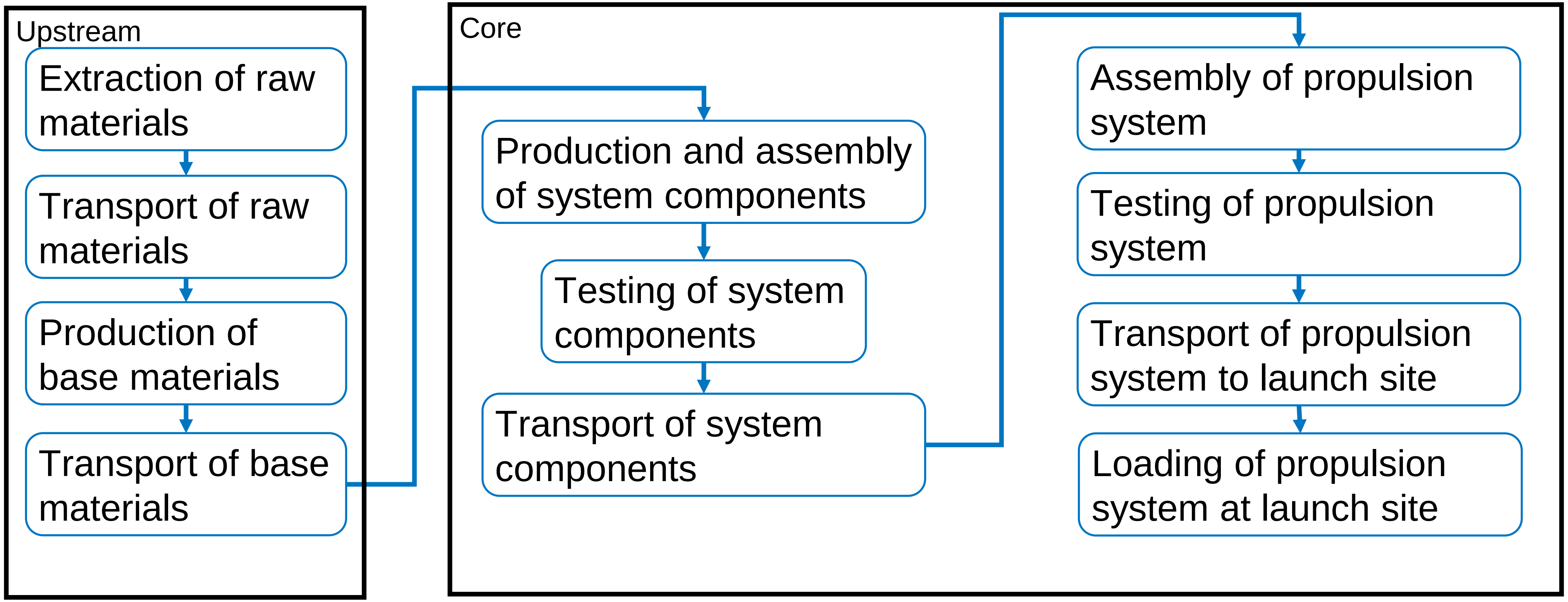
Goal and scope definition

- **Goal**: *To make a comparison between the environmental, social and economic impact of the production, assembly and testing of conventional and novel monopropellant systems in a 150-kg class satellite, considering hydrazine, ASCENT, LMP-103S and 98% hydrogen peroxide as the propellant options.*

- **Functional Unit:** *One monopropellant system in fulfilment of the propulsion system requirements set for a case study of a 150 kg Earth observation spacecraft.*

System boundaries

- Following recommendations from ESA LCA handbook for LCA of equipment production: cradle-to-gate including energy usage and waste treatment



Impact categories: SSSD LCIA EF3.0 Crossover

Name	Reference Unit
Acidification	mol H+ eq
Climate Change - Global Warming Potential 100a	kg CO2 eq
Economic Impact - Single Score	EUR 2000
Ecotoxicity, freshwater	CTUe
Eutrophication, freshwater	kg P eq
Eutrophication, marine	kg N eq
Eutrophication, terrestrial	mol N eq
Human toxicity, cancer	CTUh
Human toxicity, non-cancer	CTUh
Ionising radiation	kBq U-235 eq
Land use	Pt
Ozone depletion	kg CFC-11 eq
Particulate matter	disease inc.
Photochemical ozone formation	kg NMVOC eq
Resource use, fossils	MJ
Resource use, minerals and metals, ultimate reserve	kg Sb eq
Social impact, single score	Social Score
Water use	m3 depriv.

Key assumptions

- All components are considered TRL 9: development phase is out of scope
- Propulsion system assembly in The Netherlands
- Launch from Kourou, French Guiana
- 5% mass cut-off for included components
- System components sourced from commercial suppliers, with nation-level locality (e.g. valves from Moog in the USA)
- Component-level LCI based on publicly available data and company contacts where possible
- Social impact only assessed for core activities

Life Cycle Inventory

- Most core processes are new additions to SSSD
- Most upstream processes from ecoinvent, some from SSSD
- **Three new upstream processes: production of iridium, rhenium and 98% distilled HP**

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New process (Core)	Location	Included for
Alumina/Iridium Granular Catalyst	EU	Hyd., EILs
Alumina/Platinum Granular Catalyst	EU	HP
Catalyst Bed Heater - Coiled - Inconel Sheath	FR	All
Diaphragm Propellant Tank - Spherical - Al5254	US	HP
Diaphragm Propellant Tank - Spherical - Ti6Al4V	US	Hyd., EILs
Fill/Drain Valve - Low Pressure - Stainless Steel	US	All
Flow Control Valve - Double Seat - Stainless Steel	US	All
Loaded Minisatellite Propulsion System (various prop.)	GF	All
Minisatellite Propulsion System – 4x1N (various prop.)	NL	All
Seamless Tubing – Stainless Steel	UK	All
Thruster – 1N (various prop.)	US/EU/SE	All
Thruster Combustion Chamber - 1N - Inconel	US	Hyd., HP
Thruster Combustion Chamber - 1N - Iridium/Rhenium Alloy	US	EILs

6.
Preliminary Results

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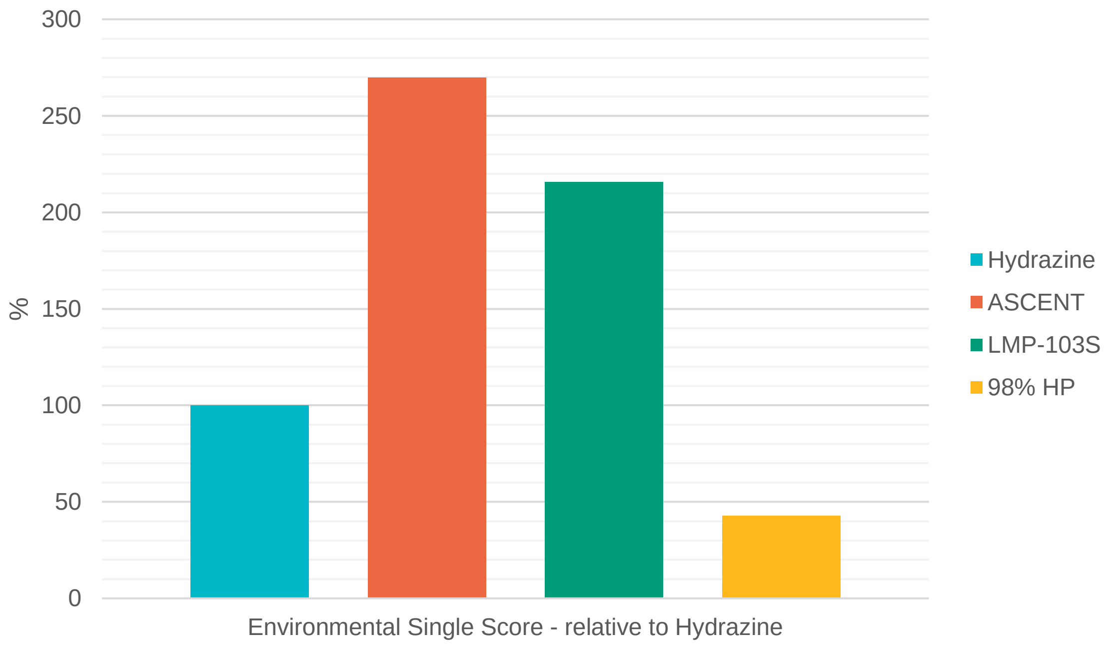
Preliminary E-LCA results

- ASCENT system scores worst overall
- Major contribution of water usage related to propellant production
- Single score calculated based on Importance of Impact Magnitude / EU Citizen



DISCLAIMER: results yet to be validated

Preliminary E-LCA results

- LMP-103S system scores worst in 9 categories
- ASCENT system scores worst in 3 categories
- Hydrazine system scores worst in 3 categories
- 98% HP scores worst in 1 category

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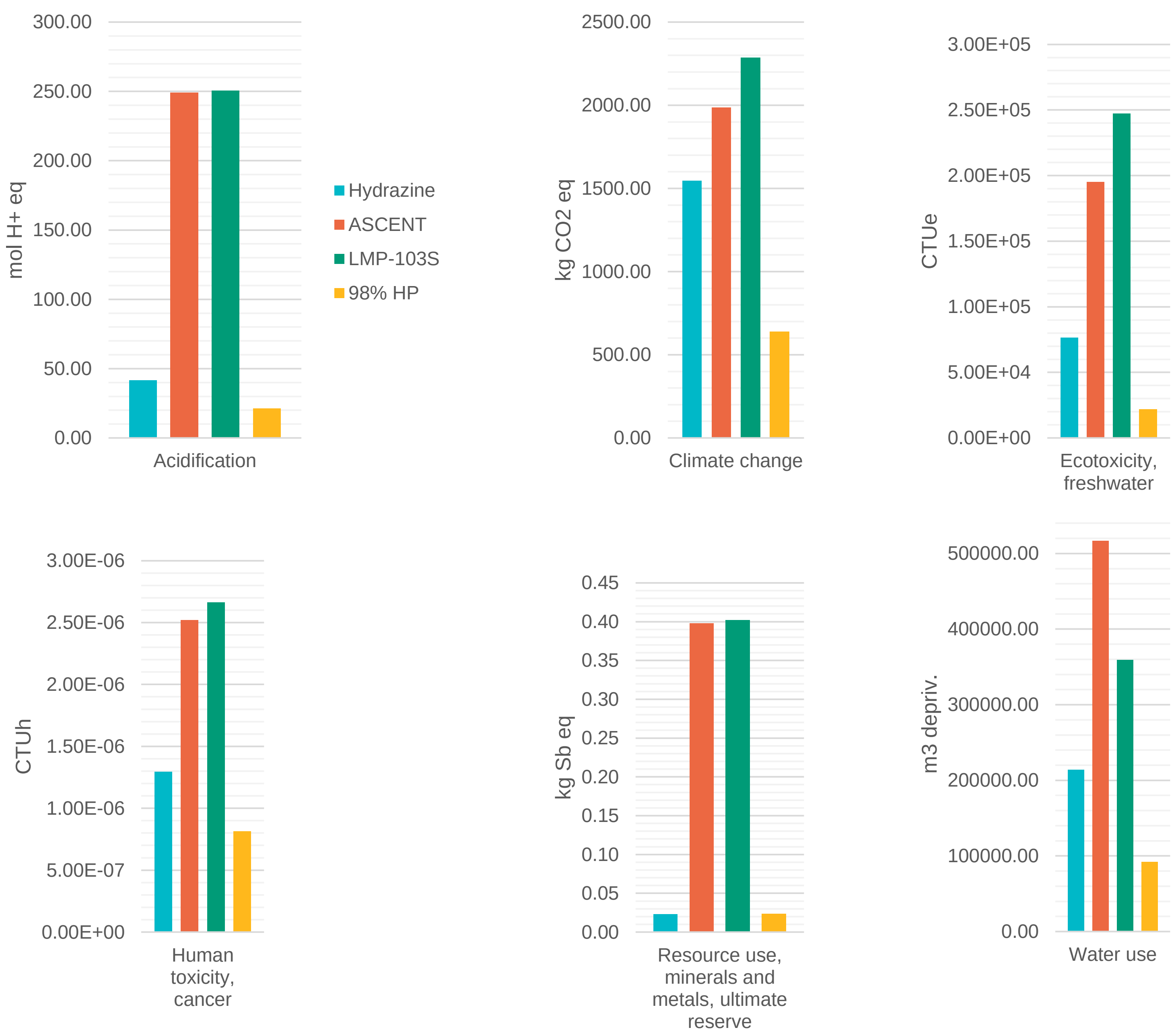

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Driving processes

Extraction of iridium

- Used in EIL thrusters
- Co-product of platinum extraction
- Extraction in Russia and South Africa
- Leading contribution for 6 categories

Production of EILs

- Energy intensive: water and fossil resource depletion
- Leading contribution for 5 categories

Extraction of rhenium

- Used in EIL thrusters
- Co-product of molybdenum extraction
- Leading contribution for 2 categories

Clean room fuelling

- Currently based solely on hydrazine process
- Major contributor for hydrazine’s impact
- Leading contribution for 2 categories

DISCLAIMER: results yet to be validated

7.
Conclusion

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Key findings so far

- Life cycle inventory based on open-source data limits research scope and reliability
- Usage of refractory and platinum-group metals in combustion chambers for EILs greatly increases their environmental impact
- 98% hydrogen peroxide seems to have smallest environmental impact, with key assumption that flight-ready hardware exists

Next steps

- Finalizing social and economic inventory and impact analysis
- Estimating uncertainties
- Validating and interpreting final LCSA results

Thank you for your attention

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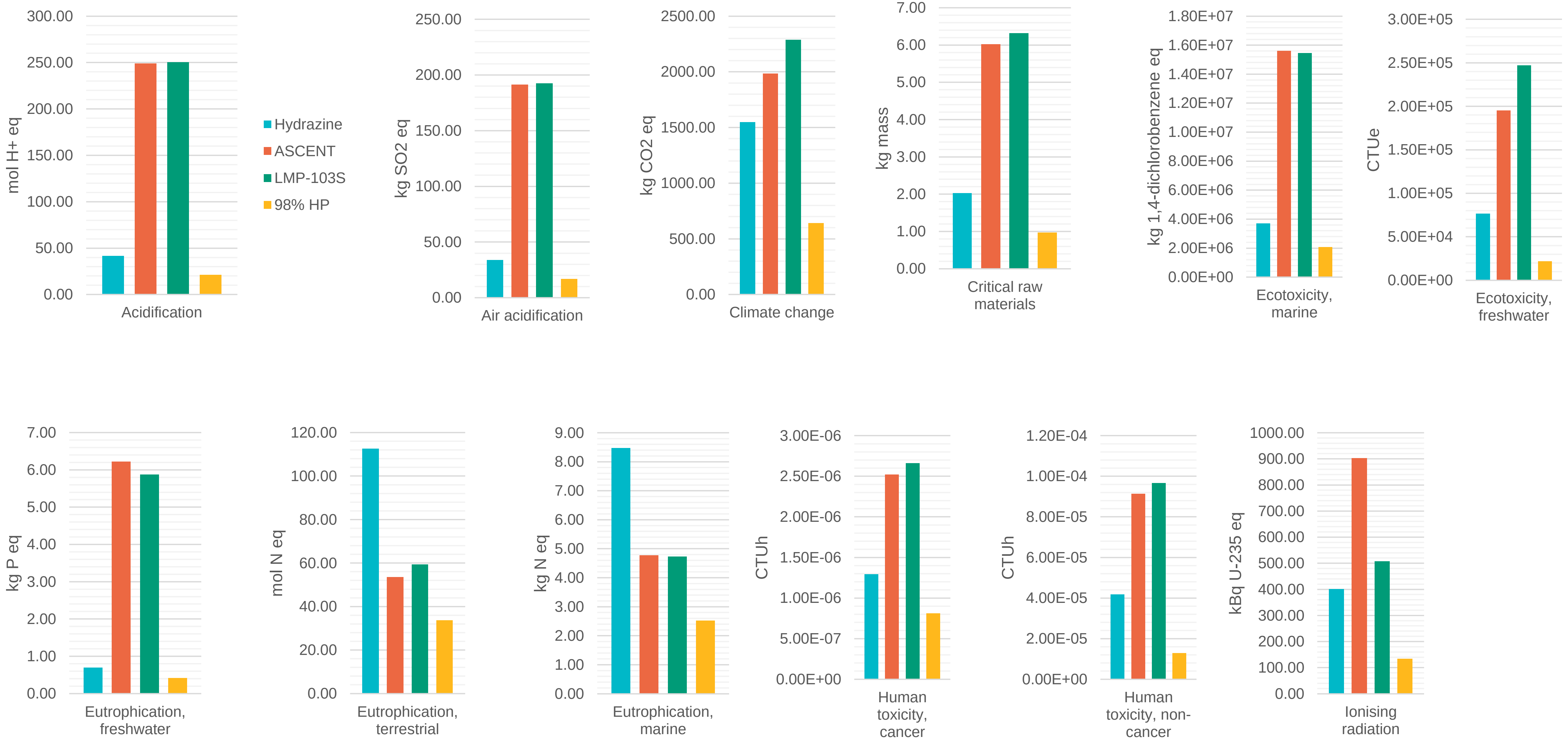
Back-up slides

Monopropellant trade-off

Criterion / Weight	Isp (s) 5	Availability 4	Complexity 4	Density (kg/m^3) 3	Safety 3	Storability 2
Hydrazine	225-250	Nominal performance	Nominal performance	1010	SCAPE required	Extensive heritage
98% Hydrogen peroxide	190	No modern flight-proven systems, extensive documentation and wide propellant availability	Different catalyst and preheating required, system is being developed	1440	Mild toxicity, mild explosivity	Restrictive material compatibility, but high concentration is more stable
90% HTP/ethanol blend	195.6	No modern flight-proven systems, limited documentation but wide propellant availability	Different catalyst and preheating required	1427	Mild toxicity, moderate explosivity	Restrictive material compatibility, and low concentration is less stable
LMP-103S	254	Broad heritage, extensive documentation on SkySat, but limited propellant availability	Different catalyst and preheating required, system has been developed	1238	Low toxicity, mild explosivity	Proven lifetime of 5+ years, wide material compatibility
FLP-106	258	No heritage, limited documentation and limited propellant availability	Different catalyst and preheating required, high reaction temperature	1357	Low toxicity, mild explosivity	Assumed lifetime of 5+ years, wide material compatibility
ASCENT	260-280	Limited heritage, limited documentation and limited propellant availability	Different catalyst and preheating required, system has been developed	1470	Low toxicity, mild explosivity	Proven lifetime of 5+ years, wide material compatibility
SHP163	276	Limited heritage, limited documentation and limited propellant availability	Different catalyst and preheating required, high reaction temperature	1400	Low toxicity, mild explosivity	Unknown
GEM	283	No heritage, limited documentation and limited propellant availability	Unknown, but most likely requires similar changes to ASCENT	1510	Unknown	Unknown
Nitrous oxide	206	No heritage, limited documentation but wide propellant availability	Different catalyst and preheating required, flame arrestor required	745	Asphyxiant and potentially explosive	Restricted storage regime, pressurized
HyNOx	303	No heritage, limited documentation but wide material availability	Separate ignition, active cooling and flame arrestor required	879	Asphyxiant and potentially explosive	Restricted storage regime, pressurized and detonable
NOFBX	350	No heritage, limited documentation but wide propellant availability	Separate ignition, active cooling and flame arrestor required	700	Asphyxiant and potentially explosive	Restricted storage regime, pressurized and detonable
Water electrolysis	325	Limited heritage, limited documentation but wide propellant availability	Different system architecture, but flight proven	998	No hazards	Widely storable

E-LCA results



E-LCA results