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Performance comparison of green propulsion systems for future Orbital Transfer Vehicles

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ABSTRACT

This paper explores the relevance of a new class of upper stages commonly referred to as Orbital Transfer Vehicles (OTVs) or Kick-Stages, and the importance of green propellants in the development of such systems. Orbital Transfer Vehicles are currently developed for diverse applications by many entities and are expected to have a major impact in the future of space missions and overall space sector. Such systems are commonly connected to the topic of On-Orbit Servicing with the promise of unlocking new missions, including active space debris removal, multi-payload to multi-orbit delivery, in-orbit experiments, in-orbit refuelling and other generic services. Green propulsion is an increasingly prevalent trend in the space industry that has experienced significant growth in recent decades with the main objective of identifying suitable alternatives to commonly used, toxic liquid propellants for in-space applications. The study investigates the synergies between the two themes, underlining the advantages that a widespread use of green technologies could bring to the overall sector, but also examining the final benefits to the system design of OTVs. Due to the numerous and challenging propulsive system requirements associated with these systems, green technologies are analysed to determine their advantages and disadvantages in comparison with current concepts, outlining current trends and expected future developments. The focus is on attainable performances of propulsion systems with respect to the required dry and inert mass. Various architectures of the different green alternatives based on hydrogen peroxide and the more peculiar self-pressurized propellants are proposed, exploring green propellants-based designs that can offer synergies and advantages over classical ones. These new architectures offer performance comparable to classical and widely available toxic alternatives and present the important advantage of using easy-to-handle propellants. The development of such new options has the potential to enable innovative future designs by improving mass and size requirements of new propulsion systems, thereby enhancing the current landscape.

1. Introduction

In recent years, there has been a remarkable exponential growth of the so-called "new space" economy, fuelled by a significant reduction in payload cost, now constituting a fraction of the price observed a few years ago. The growing accessibility of space benefits new research and developments, in a virtuous circle that is boosting the sector economy, fostering a sustainable environment for numerous companies to prosper [1–3].

The main motivation behind the rapid decline of access to space-related costs is primarily connected to the partial privatization of the sector and especially to the development of new, reusable, and performant first stages. These systems are and have historically been the most critical and complicated components in the space race, and for these reasons in the past decades a great amount of research has been spent to increase the existent overall capabilities. The introduction of recurrent launches and reusability have substantially reduced the cost of access to space, opening the market to new and unexpected players [4]. New nowadays common developers of space systems, once hard to imagine in this position, include universities independently leading low-budget development of CubeSats and small satellites [5], emerging countries and especially numerous private developers of small satellites constellations accessing the navigation, telecommunication and Earth observation markets [6]. While the technologies behind the booster stages have evolved to reduce the cost and include reusability, the capabilities of the upper stages have remained stable, and these systems are experiencing a new spring of development only in the last few years to cope with arising challenges and market requests [7]. For example, to

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date the spacecrafts' final orbit insertion is typically delegated to independent solutions and the situation has created an ideal environment for some companies to thrive offering the service of delivering small satellites and other payloads in their destination orbit, relieving them from the burden of requiring an internal propulsion system. In addition, in the last few years, there has been a growing interest for research on an emerging set of capabilities, commonly referred to In-Space economy, Space Logistics or On-Orbit Servicing [8,9].

To address the new challenges, there are various projects by public but especially private entities, planning on developing multi-purpose Orbital Transfer Vehicles (OTVs), capable of facing the current and future challenges. These devices are better described in Section 2, together with the arising requirements for their propulsion systems. The evolution of the overall space sector necessitates a maturation of general capabilities, but also by an acknowledgement of existent issues. It is well-known how the space debris issue is becoming relevant [10], and the environmental impact of launches is under scrutiny [11]. On top of this, it is renowned that propellants commonly utilized for in-space propulsion, although performant and consolidated technologies, are toxic and dangerous for human health and environment [12]. These propellants, although a potential risk for the sector, have never caused dangerous accidents. However, the management of the compounds during ground operations is difficult, requires long times and is especially expensive. In the perspective of decreasing the cost of ground operations, but also of creating a more sustainable environment, there is a spread desire of switching to safer compounds, commonly referred to as green propellants. Although there is not a shared and clear definition of green propellants, the adjective is commonly used to refer to compounds that are the least harmful for humans and environment, especially in terms of toxicity [13,14]. Section 3 describes the topic of in-space propulsion, the drive behind green propulsion and the currently most relevant alternatives.

Finally, Section 4 delves into the intricacies of the various green propellants-based options, describing the potentialities of the alternatives compared with conventional heritage systems. The analysis demonstrates that propulsion systems entirely based on green propellants can offer synergies and potential advantages over currently used toxic propellants. Various propulsion system architectures are examined, and the investigation emphasizes that, particularly during the early stages of design, evaluating propellant performance alone may not adequately determine the true convenience of one system over another.

2. In-space economy and the orbital transfer Vehicles

The last few years have seen a steep increase in the number of launchers of various size being developed, with a particular focus on the small-size class [15,16]. Numerous emerging stakeholders have ventured into the sector, committing substantial financial resources without a definitive indication that the market will reward all of them. The systems being developed are expected to bring to orbit, especially Low Earth Orbits (LEO), a significant influx of new objects with very diverse final purposes. In addition, the number of services offered or promised in orbit is growing [8]. In this framework, it is identifiable in the sector the trend of developing a great number of systems belonging to a new class of upper stages, generically referred to as Orbital Transfer Vehicles (OTVs) or Kick-Stages, dedicated at enhancing the capabilities of in-space missions and enabling new concepts. The current availability of such systems, shown in Fig. 1, is limited but promises to quickly increase. Historically, only a handful of systems have been developed to perform missions such as multi-payload delivery or support to objects already in orbit. Commonly, these were independent and extremely expensive devices, such as the Space Shuttle, now decommissioned, or added upper stages to existing rockets, such as the Fregat or the Dragon Capsule, both still in service. Fregat, in particular, is a precursor of systems now classified as OTVs for its spaceborne nature and similar class of missions. Nowadays, most of the launching services have

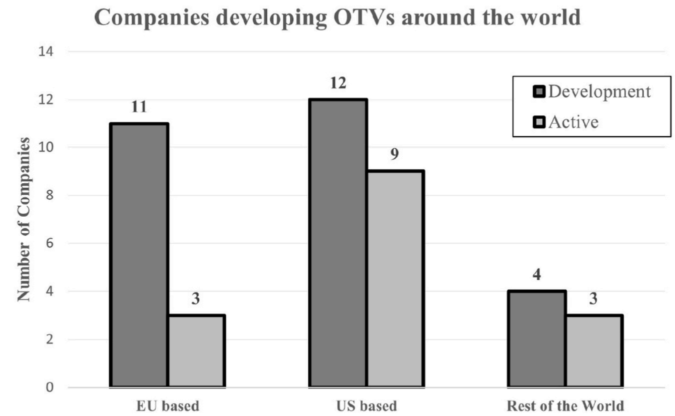

Fig. 1. Number of companies with active Orbital Transfer Vehicles or pursuing the development of new systems for different uses as per 2023. Limited information regarding new private developments in China and Russia. List of systems in Supplement Material.

developed or are in the process of developing systems similar to Fregat to expand the range of services offered to their customers. A great number of new systems, instead, are designed to be complementary and supporting to the growing launch sector, but remaining independent, promising to further develop once space economy will fully-develop also including the Moon.

While every newly developed system is typically tailored to specific scenarios or missions, it is noteworthy that they frequently possess sufficient versatility to be adaptable for various conversions in the future, often requiring only minor modifications. A key example is the evolution of multi-orbit visiting and docking capacities. Upon their comprehensive implementation and integration into a system, these capabilities will facilitate various missions such as satellites' re-fuelling, repair, inspection, orbit raising or even forced decommissioning [9,17].

The devices currently under development constitute a very diverse group, with systems' capabilities spanning from LEO orbit inclination change to cislunar activities. Despite their broad array of functions, the functionalities are frequently consolidated within the expanding sphere of the in-space economy. The new segment of the space sector aims at creating an ecosystem composed by very broad services offered directly in orbit. Various roadmaps exist, created by many important National Agencies [8,9], that have identified several segments that are delineating in the sector, although at various levels of maturity. Fig. 2 lists only the major identified branches that are in development or have been proposed by companies and agencies [8,18]. Most of the shown segments necessitate dedicated OTVs to be further developed, and this justifies the broad number of ventures attempting at fulfilling this predicted market request.

2.1. New requirements for future orbital transfer Vehicles' propulsion systems

The wide set of missions and capabilities included in the wide umbrella of in-space economy or on-orbit servicing include concepts that are not a complete novelty. Many ambitious missions of the past such as the Apollo Program, the construction of the International Space Station and the periodic cargo transportation are all notable examples of capabilities that many companies are now trying to develop for a wider availability. The difference of the present situation is that the sector is now primarily dominated by private entities, while public institutions are actively involved in the formulation of standards, policies, and regulations. The space logistics sector is anticipated to grow into a multi-billion dollars in the next decades [20], therefore it is essential to make the current regulations effort.

Among the many existent concepts, the great majority is at different

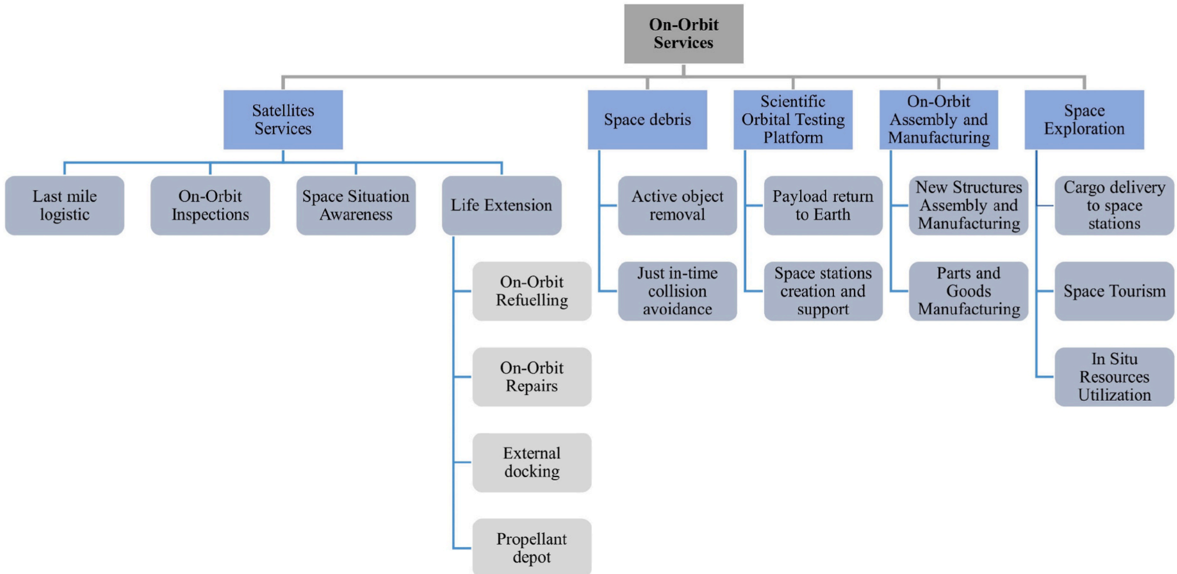

Fig. 2. On-Orbit Servicing Segments identifiable in the sector [3,8,9,17–19]. The high-level segments are shown in blue, major developments proposed in dark grey and solutions under development in term of missions toward the goal in light grey. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

but still early phases of development, although a few companies already offer some services in market, especially related to last mile delivery, as shown in Fig. 3. A more comprehensive list of entities in the pursuit of developing an OTV for diverse applications is shown in supplement material.

Predicting the evolution of widely offered services in the fully developed sector is theoretically impossible. There is a significant risk of venturing into currently impossible scenarios. The establishment of the Artemis Program and the realization of the Lunar Gateway Station will mark a significant milestone in achieving the most ambitious scenarios, which encompass the creation of a sustainable economy reliant only on space-based resources [21]. However, relying on statistics related to spaceborne devices provides a limited perspective on the sector's growth. Numerous companies are currently focused on developing fundamental building blocks for this emerging economy. The trajectory of the satellite population in orbit is relatively more foreseeable. The substantial rise in objects is projected to continue for at least the upcoming decade, occupying Low Earth Orbits (LEO) and subsequently extending to Medium Earth Orbits (MEO), Geostationary Earth Orbits

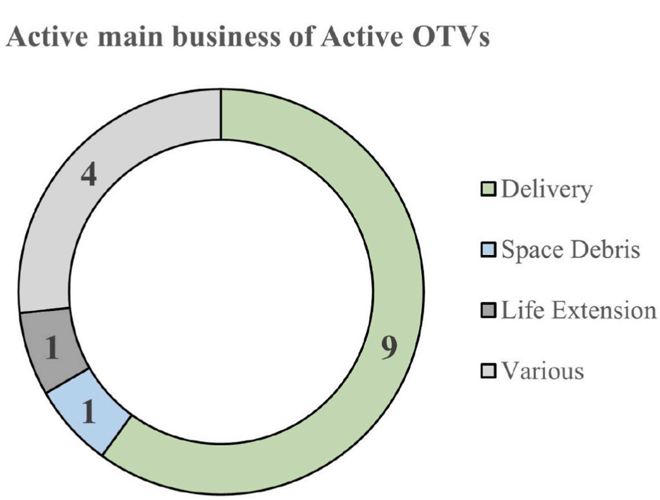

Fig. 3. Area of focus of active OTVs around the world. Details of OTVs in supplement material tables.

(GEO) and up to Lunar Orbits (LO). This extended orbital utilization, beyond stretching the current capabilities, increases the growing concern of addressing the issue of space debris. Many companies are actively developing OTVs with the exact purpose of tackling the challenge of reducing the number of uncontrolled objects in orbit by decommissioning them.

Most of the space logistics is funded around the development of new systems more capable and possibly more performant than current designs. The OTVs will cover the role of enabler of these new mission concepts and will nurture the real development of the entire sector. The concept behind the systems dedicated to multi-satellites delivery is very similar to the Fregat upper stage, a versatile Russian device that overall succeeded more than 50 times in a decade [22]. The true challenge associated with establishing a healthy in-space economy, however, lies not only in achieving the ambitious predicted outcomes, but also in ensuring the affordability of the proposed missions for a wide range of customers. Historically, complex missions similar to those proposed by certain companies have been primarily within the realm of high-budget institutional projects. However, the forthcoming space economy will need to operate and develop within more constrained financial parameters [19].

The advancement of the novel OTVs must therefore evolve with specific focus on the expenses associated with not just the system itself, but also the involved processes throughout the entire lifecycle. This includes, especially.

- Overall cost of the various composing systems, with reduced time from design to integration.
- Versatility of devices to be able to perform different missions with minor reworks.
- Ground operations with a reduced cost and leading time.
- Broad and easy systems, subsystems, and components availability.

The critical subsystems, particularly the propulsion system, will bear the impact of the challenges associated with these novel systems. Its design choices can notably influence and impact both the cost and performance of the new systems. The overarching capabilities of the OTVs will shape the necessary system performances, in addition to the requirements that the propulsion system should be capable of adapting to a wide range of missions. Table 1 summarizes the arising challenges

Table 1
New high-level propulsion system requirements of future OTVs.

OTV Challenges	Associated High-level Requirements
Multi-orbit missions	• Adaptability to different missions • Multiple thrusters' ignition capability • Long coasting phases without loss of performance (days/weeks)
Docking and Proximity Operations	• Delivery of small impulses (thrusters capable of small Minimum Impulse Bit) • Thrusters with short response time • Precise and controllable thrust direction • Manoeuvres fine-tuning
Far orbit missions (MEO, GEO, Lunar)	• High thrust engines if chemical • Long operating thrusters if electrical (months) • Long propulsion system operations lifecycle (months/years) • Long coasting phases between ignitions (days/weeks) • Non-cryogenic propellants • Reliable ignition and shut-down phases with remote controls
High ΔV budgets	• High propellant throughput the engines • High-capacity tanks • High specific impulse
Reduced ground operations cost and complexity	• Non-toxic propellants • Propellants not requiring dangerous handling procedures (compatibility with equipment and explosion sensitivity) • Off-the-shelf, ready-to-flight components

and the associated high-level requirements that new components composing the systems will need to meet.

It is foreseeable that designing a modular framework, wherein tanks or engines can be attached or detached based on mission needs, could enable a broader spectrum of potential missions using a single system design (Fig. 4). Such systems, however, require particular care in design, harmonization and optimization. The possibility to assemble and integrate different components depending on the necessity could unlock unmatched flexibility to the resulting overall propulsion systems at the cost of a longer and more difficult design phase, and likely a non-optimal performance optimization for many scenarios. The possibility to add more tanks without major rework to the propulsion system, for instance, could give the OTVs more total impulse to reach higher orbits, increasing the total impulse.

3. In-space propulsion challenges and green propellants

The propulsion system plays a particularly crucial role in ensuring the accurate and efficient functioning of any spacecraft. The OTVs are often designed to offer the payloads some services, for instance relieving them from the complexities of internal dedicated propulsion systems. Consequently, the demands on the OTVs' own system become more rigorous and complex.

A typical propulsion system is generally designed to fulfill two primary functions: execute key maneuvers for inserting the device into orbit and manage the device's attitude and orientation. These two tasks are commonly carried out by two separate sub-systems, referred to as the Main Engine (ME) and the Reaction Control System (RCS). The design of these subsystems depends on several factors, including the overall dimensions of the system and the anticipated capabilities in space. Depending on the spacecraft's capabilities, if docking and proximity operations are anticipated, an additional optional system consisting of small thrusters may be included. These thrusters would be dedicated to exclusively performing these functions, since the precision of thrust, manoeuvre duration and response velocity for proximity operations is extremely high and would impose strong design constraints to RCS or ME. For these components, as well as for the RCS, the key parameter is how short and precise a manoeuvre can be, commonly referred to as Minimum Impulse Bit (MIB).

The quantity of propellant required for each mission is closely tied to the mission's requirements, the propulsion system's performance, and the selected propellants, as visible from the classical rocket equation:

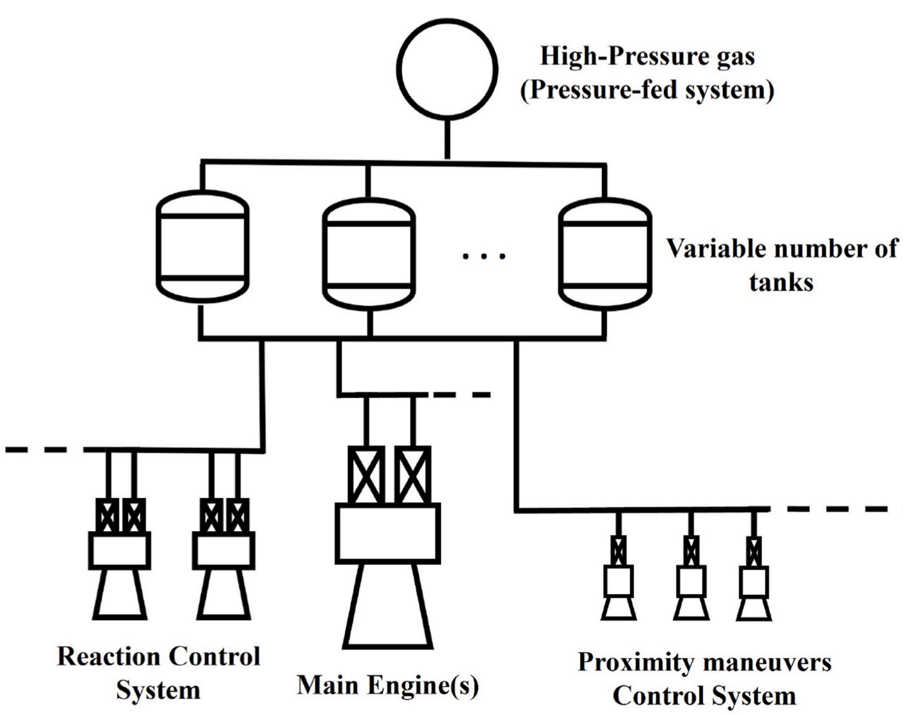

Fig. 4. Simplified diagram representing an example of a modulable propulsion system.

$$m_p = m_0\left(1 - e^{-\frac{\Delta V}{g\, I_{sp}}}\right) \quad (1)$$

The main contributors are the total mass of the entire upper stage (m_0), including the propellant mass (m_P), the mission requirements (ΔV) and the performance of the propulsion system (I_{sp}). The initial two factors are both constraints and substantial mission requirements simultaneously. These aspects are typically established and refined during the initial design stages.

The challenges summarized in Table 1 pose great strain on the commonly available design choices, hence most of the companies pursuing new OTVs design often opt to design also a dedicated propulsion system.

A particularly common design choice in the sector for long and far missions, such as GEO and interplanetary cases, is the utilization of electric propulsion systems [23]. While these devices have unbeatable performances in terms of propellant utilization efficiency, their drawback is that thrust levels achievable with these technologies are extremely low. Missions based on such systems require long transfer times and nowadays very high-power consumption, often not ideal for other types of constraints. The present study is focused on chemical propulsion, and especially on the so-called green propulsion field, that in the last few years is often mentioned and explored.

3.1. Green propulsion

Green propulsion is a field of research based on decades of efforts to discover novel propellants and their associated technologies. The goal is to find efficient compounds in terms of specific impulse and propulsion parameters that can improve the current situation, but also with the least impact on human health and the environment throughout their entire lifecycle. These new propellants are supposed to become good alternatives to the toxic Hydrazine and derivatives, the most utilized chemical propellants for in-space propulsion. Even though such toxic propellants have never caused proved accidents, their inherent costs of handling and hazard management cause diffused concern and the desire to eliminate them or drastically reduce their usage in space operations [13].

The overall green propulsion research has evolved together with the sector challenges and new technologies have often been developed to cope with some of the challenges summarized in Table 1, especially versatility of usage, ground operations simplification and cost reduction. There exist many dozens of options, some more advanced than others for different applications [12,24].

The definition of *green* is not fully defined; however, it is commonly utilized to refer to compounds with reduced impact to human health and the environment, and that can be handled without the utilization of invasive and complex procedures. Compounds of the *green* family are commonly categorized as liquid propellants and divided in those that can be used only in monopropellant mode, usually a better fit for small satellites propulsion systems or for reaction control systems for their commonly limited performance in terms of specific impulse; and those that can be used in bipropellant mode, usually more performing and applicable to wider requirements, but more complicated component-wise and in integration. Propellants that can be used in multiple ways, i.e. monopropellant, bipropellant and sometimes even for electric thrusters are rare and the systems able to implement them are called multi-mode. Such systems are not common and exist only a few examples based on hydrazine.

There are numerous studies that analyse different green propellants for their present and future applications [25,26]. The comprehensive review of such compounds exceeds this study purpose, and since the extension of *green* is not fully defined, in the study it is intended as part of the family any compound not listed as toxic or dangerous for human health if managed properly, that does not require special or complex handling procedure during ground operations, and that is not listed as extremely dangerous for the environment by international organizations as reported in review studies [27,28].

Research has focused for years on energetic compounds to use as monopropellants, since the market share of small satellites is growing, but recently there are many green options also for bipropellant systems [24]. One of the main constraints of green bipropellant systems is that, in terms of available and non-harmful oxidizers, options are restricted to two compounds: highly concentrated Hydrogen Peroxide (High Test Peroxide, or HTP) and Nitrous Oxide [29]. The very narrow choice makes the development of new bipropellant systems divisible in two categories, because depending on the selection, the overall design must change radically, as following section of design choices shows. Table 2 summarizes the features of the two leading oxidizers in terms of benefits and disadvantages.

The propellants analysed in the present study are various and applied in monopropellant, bipropellant, and multi-mode. Table 3 summarizes the properties of the compounds selected for the study, with associated theoretical performance. The theoretical performances have been obtained using the open-source software NASA CEA [30] with combustion chamber pressure of 10 bar, frozen throat combustion, and expansion ratio in vacuum of 100 for RCS thrusters and 300 for ME. HTP and Hydrazine monopropellants are not compatible with high values of expansion ratio for the presence of condensed species in the nozzle during expansion. For these propellants, the expansion ratio has been decreased to 100 for the ME and 50 for the RCS.

For all the alternatives proposed, the RCS specific impulse is naturally lower for the decreased expansion ratio, connected to these thrusters reduced size compared to larger main engines. In the study, it is added a further efficiency of 95 % to the theoretical value of RCS specific impulse (i.e. the RCS theoretical specific impulses are reduced by 5 %). The efficiency is applied to account for the common utilization of RCS thrusters in pulsed mode, where transient losses are more significant, resulting in decreased overall performance. The efficiency value is estimated and is representative of the effects of pulsed operations but should not be considered as a conclusive value for any design, as it depends on design specifications and pulses duration [31]. The performances listed in Table 3 are to be considered theoretical and non-optimized. Finalized thrusters can reach different values.

Among the various other green alternatives not analysed in the present study, it is important to highlight water propulsion, which, although is still in its early stages of development, holds significant potential benefits for the sector. Water is easily transportable, can be stored indefinitely, is relatively abundant in space, and is simple to resupply. These systems commonly function through the initial electrolysis of water, followed by the combustion of hydrogen and oxygen—a highly efficient reaction. Although these systems currently exhibit complexity and necessitate further research, their potential applicability to future systems is undeniably promising [35].

Table 2
Green oxidizer options comparison.

Hydrogen Peroxide		Nitrous Oxide	
Advantages	Disadvantages	Advantages	Disadvantages
• Compatible with many fuels • Hypergolic behaviour • Low-Pressure storage • Similar to heritage technologies • Operable in monopropellant mode, easy to decompose	• Materials Compatibility Issues • Self-Decomposition over time • Lack of certified supply chain for large quantities	• Broad availability • Compatible with many fuels • Operable in monopropellant mode, but hard to decompose	• High-Pressure storage • Low density • Ignition requires external devices

Table 3
List of green propellants analysed in the study. Physical properties at 20 °C. Theoretical performances of known species calculated using the open-source software NASA CEA [30]. Performances of proprietary compounds taken from references. The asterisk refers to the cases with decreased expansion ratio because of presence of condensed species during expansion.

Propellant	Type	Density [g/cm^3]	Specific Impulse (ME)	Specific Impulse (RCS)
Hydrazine	Monopropellant/ Multimode	1	231 s*	217 s*
Hydrogen Peroxide (HTP, 98 % H_2O_2)	Monopropellant/ Multimode	1.43	190 s*	178 s*
ASCENT (ex AF-M315E) [32]	Monopropellant	1.47	260 s	250 s
LMP-103S [33]	Monopropellant	1.24	260 s	240 s
NTO/MMH	Bipropellant	1.44/ 0.88	339 s	315 s
NTO/Hydrazine	Bipropellant/ Multimode	1.44/1	345 s	320 s
HTP/RP1	Bipropellant/ Multimode	1.43/ 0.82	335 s	310 s
HTP/HIP_11 [34]	Bipropellant/ Multimode	1.43/ 1.15	322 s	308 s
N_2O/Propylene	Bipropellant	0.79/ 0.52	313 s	292 s
N_2O/Ethane	Bipropellant	0.79/ 0.34	313 s	292 s
N_2O/RP1	Bipropellant	0.79/ 0.82	308 s	287 s
HTP/Ethane	Bipropellant/ Multimode	1.43/ 0.34	340 s	314 s

3.2. Analytical model

It is developed a framework of mathematical relationships to evaluate different design choices based on common performance parameters. To investigate the effects of the main engine and reaction control system separately, but still as part of the same propulsion system, the two contributions have been investigated as part of a multi-mode propulsion system, as described in literature [36]. The fraction of ΔV budget allocated to the RCS, $f_{\Delta V}$ in Eq. (2), is an arbitrary value of 5 % of the total, value estimated for an orbital stage for which the station keeping is not the primary purpose (i.e. 95 % of the system ΔV budget is allocated to ME, and 5 % to RCS). The effects of changing this quantity are explored in the final comparison. The multi-mode specific impulse of the system, averaged on the utilization, is derived using Eq. (3). The amount of propellant needed by the reaction control system, expressed by the fraction $f_{P\text{-}RCS}$, varies according to the mission requirements, as expressed in Eq. (4). The amount of propellant needed by the main engine, $f_{P\text{-}ME}$, is complementary to the RCS fraction.

$$f_{\Delta V} = \frac{\Delta V_{RCS}}{\Delta V_{ME}} \tag{2}$$

$$I_{sp-mm} = \left[\frac{1-f_{\Delta V}}{I_{sp-ME}} + \frac{f_{\Delta V}}{I_{sp-RCS}}\right]^{-1} \tag{3}$$

$$f_{P-RCS} = \frac{m_{p-RCS}}{m_P} = \frac{1-e^{-\frac{f_{\Delta V}\Delta V}{g\, I_{sp-RCS}}}}{1-e^{-\frac{\Delta V}{g\, I_{sp-mm}}}} = 1 - f_{P-ME} \tag{4}$$

Typically, propulsion system analyses and selections tend to prioritize the specific impulse (I_{sp}) to take decisions. Undoubtedly, this parameter is crucial for identifying the most efficient technology in terms of utilization of propellant mass; however, it does not always summarize the full intricacy of the subject. While it is a relatively easy parameter, useful to promptly gauge propellant efficiency, it does not account for variations in terms of mass requisites imposed by the technologies. Nuclear propulsion, for example, has typical I_{sp} values up to an order of magnitude higher than common alternatives. Nonetheless, the entire system necessitates masses that largely exceed those of current systems. When directly comparing individual figures, this significant disparity is not emphasized.

The various design choices described in the present analysis are investigated in terms of a parameter called System Specific Impulse (I_{SSP}), used to compare different propulsion systems considering the entire wet mass envelope (m_{PS}) instead of only the propellant efficiency, Eq. (5). As the propellant fraction increases, so does the system specific impulse, irrespective of the constant specific impulse value [37,38].

$$I_{SSP} = \frac{I_{TOT}}{g_0 m_{PS}} = I_{SP}\frac{m_P}{m_{PS}} \tag{5}$$

The propulsion system mass (m_{PS}) represents the overall wet mass that considers all the components or subsystems required by the various propellants. For instance, in case of hydrazine use it is commonly foreseen the presence of heaters to avoid freezing of the compound. In the propulsion system mass, it is accounted both the mass of the heaters themselves and, if present, the additional power supply mass necessary for its operations. The propulsion system mass can be split into its contributions: the propellant mass (m_P); the hardware mass (m_{HW}) that represents the impulse-independent contribution such as the thruster, thrust frame, heat shield, piping, connections, and valves; the tankage mass (m_{tank}); and, finally, the pressurization system mass ($m_{PressSyst}$) if present in the design, as expressed in Eq. (6). The parameters f_{HW}, f_{tank} and $f_{PressSyst}$ are the respective mass fractions respect to the propellant mass m_p.

$$\begin{aligned} m_{PS} &= m_P + m_{PS-dry} = m_P + m_{HW} + m_{tank} + m_{PressSyst} \\ m_{PS} &= m_P\left(1 + f_{HW} + f_{tank} + f_{PressSyst}\right) \end{aligned} \tag{6}$$

The propulsion system mass contributions can be written in relation to the propellant mass and the system specific impulse can be rewritten as Eq. (7). The correct computation of the mass fractions depends on factors difficult to evaluate at preliminary design phases, when the propellants or architectures are selected. However, it is possible their estimation as described below.

$$I_{SSP} = \frac{I_{SP}}{\left(1 + f_{HW} + f_{tank} + f_{PressSyst}\right)} \tag{7}$$

The tank fraction depends on a multitude of factors, including the materials utilized, the structural optimization, the utilization of specific propellant management devices and the number of tanks. In the present study, tank design choices are not analysed separately and instead it has been used an estimated mass of the tank per volume of propellant stored, using common pressure vessel formulas, reported in Appendix A [31]. It has been neglected the presence of surface tension equipment. The mass of a tank per cubic meter of propellant stored, K in Eq. (8), stored at pressures of 25 bar is 60 kg/m^3, while for higher pressures is estimated at 110 kg/m^3. The impact of the tank aligns with existing components available off the shelf and considers only large samples [39,40], as reported in Appendix A. The tankage fraction also includes considerations of the impact of a modulable design by considering that, for an OTV design, it may be beneficial storing the propellants in more, smaller tanks with identical volume or mass. The number of tanks, N, depends on a multitude of factors not optimized in the present study and is defined as the total volume of propellant divided by the selected equal tank volume or, alternatively, the total propellant mass divided by the selected mass of each equal-wet-mass tank. The number of tanks is fixed at the minimum value of one and two for the monopropellants and bipropellants respectively. The tankage fraction eventually depends on the specific volume of the propellants utilized, Eq. (8). For systems involving more than one compound, it has been used the average density (ρ_{avg}) of RCS and ME, using the density of oxidizer (ρ_{Ox}) and fuel (ρ_{Fu}), with the ideal mixture ratio oxidizer-to-fuel (ROF) to calculate their required quantity, expressed by Eq. (9).

$$f_{tank} = \frac{m_{tank-dry}}{m_P} = \frac{N \bullet K}{\rho_{avg}} \quad (8)$$

$$\rho_{avg} = f_{P-RCS} \bullet \left(\frac{\rho_{Ox}\rho_{Fu} \bullet (1+ROF)}{ROF \bullet \rho_{Fu} + \rho_{Ox}}\right)_{RCS} + f_{P-ME} \bullet \left(\frac{\rho_{Ox}\rho_{Fu} \bullet (1+ROF)}{ROF \bullet \rho_{Fu} + \rho_{Ox}}\right)_{ME} \quad (9)$$

The pressurization system mass fraction has been estimated in an analogous way, using the formula for spherical tanks at high pressure [41], with all the gas stored in a single tank. The overall mass strongly depends on the pressuring gas selected, as well as on the tank material utilized. The mass of pressurization system per cubic meter of propellant to pressurize is estimated at 100 kg/m^3.

$$f_{PressSyst} = \frac{m_{PressSyst}}{m_P} = \frac{100\ kg/m^3}{\rho_{avg}} \quad (10)$$

Finally, the hardware mass fraction includes all the components of the propulsion system not comprised in the previous factors. This includes, for instance, the thrusters, valves, pressure regulator, power control box and various electrical and fluidic connections. The mass fraction strongly depends on the thrust level chosen, as well as other considerations, especially how well the RCS and ME are integrated.

$$f_{HW} = \frac{m_{HW}}{m_P} = 10\% \quad (11)$$

For the study, the hardware fraction is estimated at a conservative 10 % of the total propellant mass, Eq. (11). The factor does not depend on different configurations nor architectures; hence, it is a constant for all the various design choices.

Once the parameters are established, it is possible comparing different propulsion systems using the rocket equation in the form of Eq. (12).

$$\frac{m_{ps}}{m_0} = \frac{I_{SP}}{I_{SSP}}\left(1 - e^{-\frac{\Delta V}{g\ I_{sp}}}\right) \quad (12)$$

Finally, by using Eq. (6) and Eq. (12), it is possible to extrapolate the dry mass fraction depending on the overall mass, as per Eq. (13).

$$\frac{m_{ps-dry}}{m_0} = \left(\frac{I_{SP}}{I_{SSP}} - 1\right)\left(1 - e^{-\frac{\Delta V}{g\ I_{sp}}}\right) \quad (13)$$

The difference between studying the sole propellant fraction respect to propulsion system mass fraction is clear in Fig. 5. Studying only the propellant fraction, the impression is that very high velocity changes would be possible with enough propellant and at payload expense. This is inherently not true since the propulsion system dry mass grows accordingly. The propulsion system mass fraction is more accurate for the study of overall upper stage mass budgets. Regardless of the quantity of propellants on board, very high velocities are not reachable.

4. Design alternatives analysis and description

Various green propellants-based propulsion system architectures are proposed, described, and compared with conventional options that rely on toxic compounds. In this study, the term “architecture” is employed to denote the degree of component integration among the different subsystems [42]. The alternatives are outlined generically, and additional comprehensive analyses are required before reaching their definitive configurations, especially if the goal is reaching modulable systems.

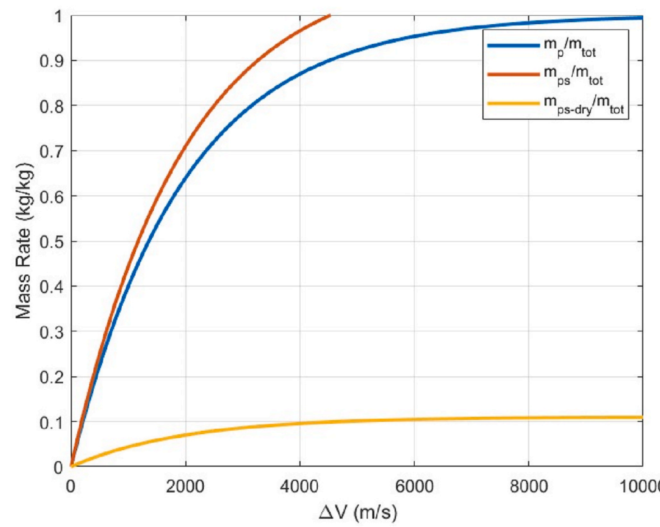

Fig. 5. Difference between showing the attainable velocity change with propellant mass fraction and propulsion system mass fraction. Curves calculated with exemplary values of I_{sp} = 200 s and I_{ssp} = 180 s.

4.1. Only-monopropellant architecture

The initial proposed architecture, shown in Fig. 6, represents the simplest approach, relying solely on monopropellant thrusters. For simplicity, a single main engine thruster has been utilized, although employing clusters of smaller thrusters would output similar outcomes. The prominent advantage of the only-monopropellant architecture lies in its simplicity: the thrusters are straightforward to operate, the potential points of failure are limited, and the overall system is simple. These systems are commonly utilized for small satellites, although historical instances have seen their application in larger devices [31,43]. They have never been employed in upper stages, as operating monopropellant thrusters at high levels of thrust becomes more challenging. Typically, these systems rely on pure hydrazine due to its exceptional flight history and performance in monopropellant mode. However, a few promising compounds have been selected and compared, summarized in Table 4.

The architecture is simple and adaptable to various changes, including modularity. The fact of having one single propellant to store allows to standardize the tanks and to attach to them as many thrusters as necessary. In particular, the system would be easily able to accommodate various thruster sizes without major modifications, for any type of manoeuvres predicted during mission analysis. Monopropellant thrusters are straightforward to scale, and applications ranging from Newtons to hundreds of Newtons are already flight proven. The thrusters require minimal support components, relying on a single feeding line and related valves. Monopropellants commonly are decomposed by catalysts before expulsion and the only precautions and variabilities between systems are related to some compound requiring reaching an optimal temperature before the process. Some types of heaters may be required, and the response time of these thrusters vary accordingly.

The comparison underscores that, for ΔV requirements ranging from moderate to high, the propulsion system’s mass fraction for this architecture becomes quickly elevated and may result impractical. The strengths of monopropellant thrusters reside in their simplicity, adaptability, and size. However, performances are low, and their application to main engines introduces an excessive requirement for propellant mass.

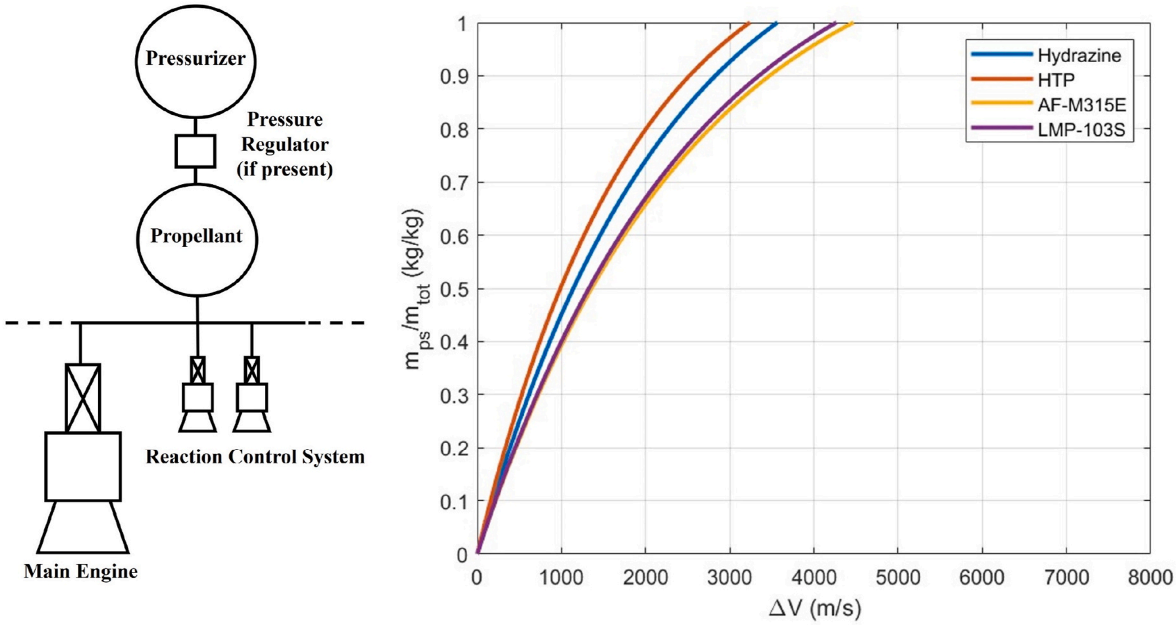

Fig. 6. Only-monopropellant architecture and theoretical performance attainable by various propellants.

Table 4
Monopropellant options analysed.

Propellant	Density [g/cm^3]	Tankage fraction	Press. system fraction	System Specific Impulse
Hydrazine	1	6 %	10 %	180 s
Hydrogen Peroxide (98 % H_2O_2)	1.43	4.2 %	7 %	155 s
ASCENT (ex AF-M315E)	1.47	4.1 %	6.8 %	214 s
LMP-103S	1.24	4.8 %	8 %	210 s

The significance of specific impulse on overall system performance remains evident, as the HTP, while dense and highly efficient in terms of mass, is a propellant with low performance capabilities.

It is immediately apparent alternatives to hydrazine present improved performance in terms of both density and system specific impulse. Their application would lead to improvements respect to classical and toxic alternative. Unfortunately, these propellants may present issues to acknowledge although beyond the scope of the study. Hydrazine and HTP are commonly and quickly decomposed by commercial catalysts without the support of external components [13], while the other propellants may need heaters to reach the ideal temperature. This element negatively affects the quick responsivity of the thrusters in the case of the presence of a connected strict requirement.

4.2. Only-bipropellant architecture

The architecture called only-bipropellant, shown in Fig. 7, is doubtlessly the most common for in-space operations, offered by all the main space systems manufacturers off-the-shelf or customized, sometimes referred to as Unified Propulsion System [44]. It is commonly sold based on the coupling between MMH (or for older systems UDMH) and NTO. It offers high performances, multiple re-ignition capability, good storability and flexibility and has dozens of flight-proven examples of various sizes [43]. The sole drawback of this design is its dependence on the toxic propellant combination.

The switch to greener options is possible and many options representing good replacements are arising. To persuade the market and stakeholders, these new solutions should not only emphasize their reduced toxicity but also their potential for improvement. The conventional propulsion systems have been developed and optimized over decades of research and use, whereas the new systems may not be fully optimized yet. For example, the adoption of multi-mode operations, as explained in the following section, is a logical evolution for some of the green bipropellant options.

For the study, compounds that could replace currently used toxic propellants with reduced re-design are selected (Table 5). In particular, the couple HTP/RP1 is probably the most researched and widespread around the world, with Korea and Europe leading new developments [45,46], and it is representative of other hydrocarbons with similar behaviour such as Ethanol. It is selected also a combination still at early phase of development, HTP/HIP_11. It is a hypergolic combination based on HTP and an ionic liquid, a promising example among many similar proposed in the sector [47].

The comparison shown in Fig. 7 demonstrates that all the analysed combinations exhibit relatively similar performances, confirming how new developments could replace hydrazine without strong impacts of current system capabilities. The utilization of non-toxic and easy-to-handle options would bring benefits to the ground operations without impairing space capacities.

Within this architecture, other factors such as system complexities, the availability of readily accessible components, the size of involved components, and cost, cover greater importance and necessitate further considerations. In particular, although studies have addressed the compatibility of HTP with various materials [48], the availability of ready-to-use components with certified compatibility is still lacking.

The only-bipropellant architecture can be integrated with additional sub-systems such as rendezvous and proximity thrusters, however the addition requires careful evaluations. First, there are many designs of small and accurate bipropellant thrusters [49,50], all are based on historical toxic propellants, hence more designs based on the new alternatives are needed. In addition, system analysts need to make careful considerations regarding the thrusters' ignition response time and the

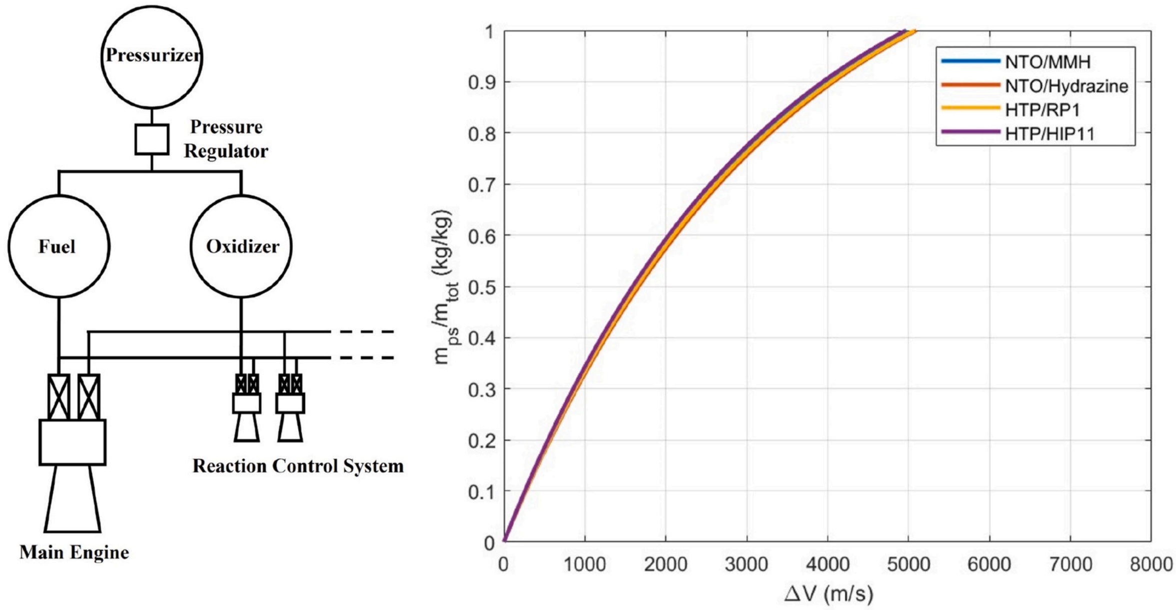

Fig. 7. Only bipropellant architecture and attainable performance comparison.

Table 5
Bipropellant options analysed.

Propellant	Density [g/cm^3]	Nominal ROF	Tankage fraction	Press. System fraction	System Specific Impulse
NTO/MMH	1.44/0.88	1.85	10.2 %	8.5 %	263 s
NTO/Hydrazine	1.44/1	1.2	10 %	8.3 %	268 s
HTP/RP1	1.43/0.82	6.2	9.3 %	7.7 %	263 s
HTP/HIP_11	1.44/1.15	4	8.8 %	7.3 %	255 s

integration of two fluidic lines and related critical components to check the compatibility with the delicate requirements of proximity manoeuvres.

4.3. Multi-mode architecture

The architecture called multi-mode (Fig. 8) is based on the use of Hydrazine or HTP as propellant component for a bipropellant, high performant and high thrust main engine and in monopropellant mode for the smaller RCS thrusters.

The goal of the architecture is benefitting from the simpler monopropellant thrusters' design and the connected reduced number of lines, valves, and components, even though their performance is significantly reduced. Given the limited ΔV budget of the RCS thrusters, the effect of reduced performances is relatively small. Given their critical role in mission success, their reliability is of crucial importance, and monopropellant systems, possessing fewer components and fewer points of failure, could be a compelling choice.

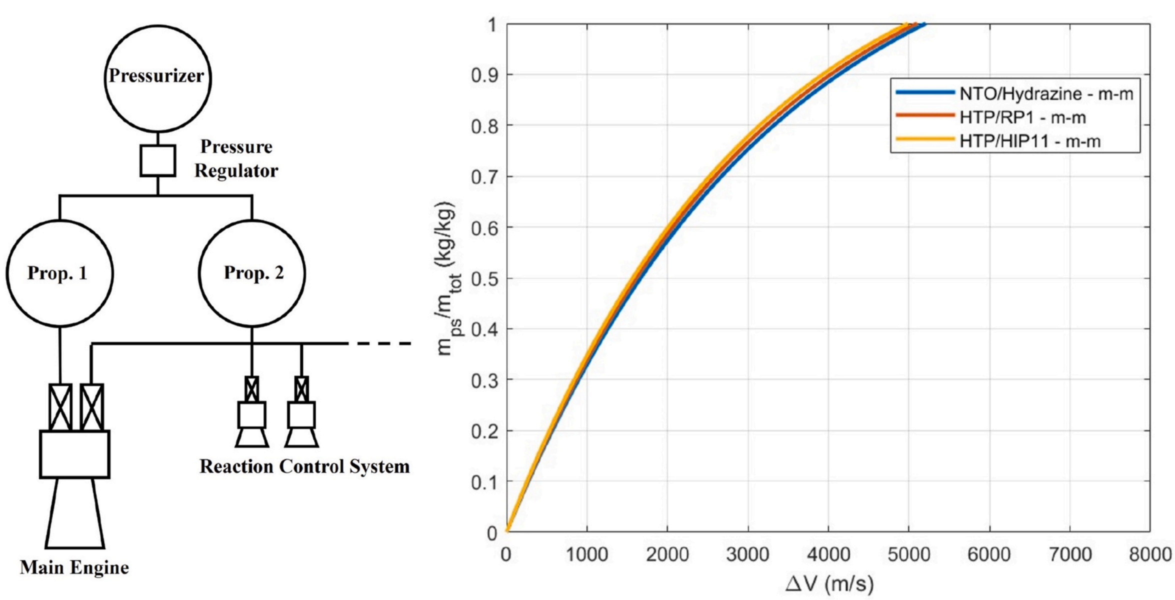

Fig. 8. Multi-mode architecture and attainable performance comparison.

Table 6
Multi-mode options analysed.

Propellant	Density [g/cm^3]	Nominal ROF	Tankage fraction	Press. system fraction	System Specific Impulse
NTO/Hydrazine	1.44/1	1.2	9.7 %	8.1 %	266 s
HTP/RP1	1.43/0.82	6.2	9.1 %	7.6 %	257 s
HTP/HIP_11	1.44/1.15	4	8.7 %	7.3 %	250 s

The analysed options, summarized in Table 6, use the same propellant alternatives of the only-bipropellant architecture. The analytical framework developed in the previous section only partially allows to highlight the real extent of the integration between the RCS and ME and the connected reduction in number and mass of components. The analysis does not introduce artificially decrements of hardware fraction masses, even though the presence of fewer components could reflect on that. To accurately decrease the hardware mass fraction, a comprehensive assessment of the number of components and their related masses is necessary. However, the study takes a conservative approach and avoids making modifications.

The architecture exhibits comparable performance to the only-bipropellant alternative, with minor differences observable. The system specific impulse of the multimode system is only slightly worse, fact connected to the low performance of the RCS monopropellant thrusters.

In general, the system dry mass is lighter, fact visible from the tankage and pressurization system fractions, but the low specific impulse of the monopropellants causes an increase in the required propellant mass dedicated to it. Even though the RCS represents only a minor fraction of the overall budget, its impact in terms of needed propellant cancels the gains in terms of mass saving from the utilization of monopropellants, resulting in overall performances almost equal to the only-bipropellant architecture.

The equality of conditions, however, can constitute itself an advantage because many other factors concur to the final choice beyond the mass fraction, including the reliability and complexity of the systems, its costs and especially the utilization of greener propulsion, all elements that the multi-mode architecture promises to improve. In addition, the utilization of a multi-mode architecture is easily adaptable to modularity. Monopropellant thrusters, especially those based on Hydrazine and HTP analysed for this architecture, are commonly less complex than bipropellant engines. Some designs of very small thrusters compatible with proximity manoeuvres requirements are already in the market [51, 52], and their integration based on a sole fluidic line and catalysts simplifies system considerations.

The technologies behind the utilization of multimode systems based on hydrazine have been known for decades. However, they have not often flown because hydrazine freezes more easily than MMH, and its combustion is less stable [31].

4.4. Self-pressurizing architecture

It is introduced in this paper the so-called self-pressurizing architecture (Fig. 9). It is based on bipropellant combustion and relies on the pairing of fuels and oxidizers possessing elevated vapour pressure at typical storage temperatures, resulting in inherent feeding pressure within the lines. Examples of such compounds include light hydrocarbons like Propylene or Ethane as fuel, along with Nitrous Oxide employed as an oxidizer, as reported in Table 7. There are not many compounds utilizable as propellants in this architecture, since vapour pressure level necessary to inject the propellants into the combustion chamber should exceed 5 bar at relatively low operating temperatures.

The undeniable advantage of this architecture lies in the absence of a separate pressurization system. The vapour pressure of these compounds is high-enough to allow the injection of the propellants in the combustion chamber, although the combustion pressure is highly constraint by this factor. The design of propulsion systems using these compounds can be different from the conventional design choices available in the market. This could include gaseous injection as well as trade-offs to utilize low-pressure combustion to achieve the optimal balance between mass and performance.

While these propellants offer relatively high specific impulse, they are, unfortunately, less dense than other liquid compounds at ambient temperatures and hence necessitate a larger tankage fraction, which, in turn, can reduce the overall performance of the propulsion system.

As visible from Fig. 9, the two examined fuels coupled with nitrous oxide exhibit very similar properties, resulting in comparable performance. Unfortunately, the compounds possess a relatively low density compared to other liquid propellants that negatively impacts the tankage fraction and consequently the overall propulsion system performance. The selection of self-pressurizing propellants must include parameters beyond the density, including the vapour pressure at operational temperatures, which contributes to determining the combustion chamber pressure, and the combustion temperature, typically high for light hydrocarbons.

The architecture shows similar feature to the only-bipropellant option in terms of modularity. Other sub-systems could be added, although further considerations are necessary regarding the existence of small thrusters, their response time, and the compatibility of the overall system with multiple fluidic lines.

Table 7
Self-pressurizing options analysed.

Propellant	Density [g/cm^3]	Nominal ROF	Tankage Fraction	System Specific Impulse
N_2O/Propylene	0.79/0.52	6.5	21.7 %	237 s
N_2O/Ethane	0.79/0.34	7.5	23.4 %	234 s

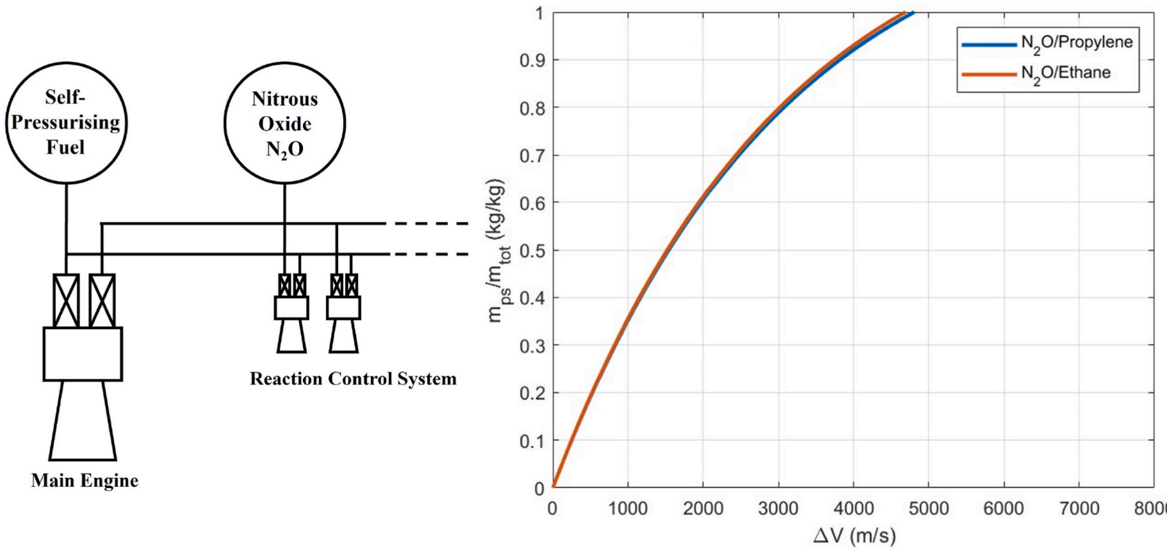

Fig. 9. Self-pressurizing architecture and attainable performance comparison.

4.5. Self-pressurizing single-tank architecture

Finally, it is introduced a new architecture that resembles the previous design, with the key distinction that one of the two propellants no longer necessitates high vapour pressure The architecture is called self-pressurizing single-tank architecture (Fig. 10) and has not, to the best of authors' knowledge, never been proven nor developed. This configuration employs one of the two propellants to pressurize itself and the other compound, reducing the number of elements present in the system and saving the related mass. Conventional fuels like RP1 or ethanol can be employed coupled with nitrous oxide as oxidizer, as well as HTP as oxidizer coupled with ethane or propylene.

The storage of fuel and oxidizer into a single tank requires additional and careful studies and research to address any potential safety concern. If the concept would prove feasible, it could result in substantial reduction of components count and size.

The architecture could represent a future innovation of green propulsion in terms of compactness; however, there are several factors to address during initial research phases. These include the safety concerns of storing two compounds closely together, the system integration and the basic research on combustion between so-different propellants.

The performances of such systems are promising, although limited by the low density of the involved compounds, as visible in Table 8. The combination based on HTP, that has a higher density, reveals the real

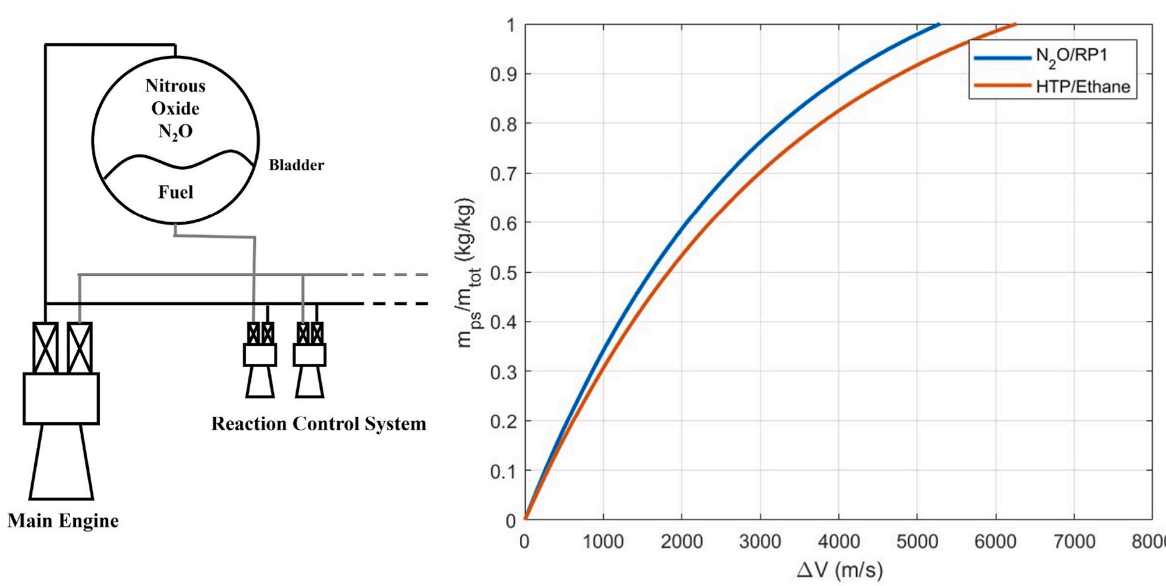

Fig. 10. Single-tank self-pressurizing architecture and attainable performance comparison.

Table 8
Self-pressurizing single-tank options analysed.

Propellant	Density [g/cm^3]	Nominal ROF	Tankage Fraction	System Specific Impulse
N_2O/RP1	0.79/0.82	7	13.9 %	254 s
HTP/Ethane	1.43/0.34	6.7	10.9 %	287 s

benefit of the architecture, showing the highest system specific impulse analysed in the study. Considerations regarding the modularity of this system are similar to the previous architectures based on bipropellant engines. In addition, the physical modelling of the single-tank behaviour during expulsion requires dedicated studies.

4.6. Overall comparison and results discussion

The concluding comparison in Fig. 11 assesses the proposed and analysed design choices between each other in terms of overall wet mass and dry mass. The analysis illustrates how some architectures can present certain mass-related advantages but overall perform all very similarly. The comparison of wet propulsion system mass, in the left side of Fig. 11 shows how the monopropellant and self-pressurizing options require a higher mass fraction respect to the other alternatives that perform all very similarly. The peculiarity of the result is that the self-pressurizing option has a high specific impulse but, as shown in the right side of Fig. 11, it requires a larger dry mass than other alternatives. The low density of the propellants causes a notable increase of the dry mass required, specifically the tankage fraction, framing it at similar performances of monopropellants engines even though the classically used specific impulse is higher.

The alternatives are additionally compared against a hypothetical reference mission to better highlight the effects of the performance differences. It has been used an exemplary OTV going from Geostationary Transfer Orbit (GTO) to GEO. The required change of velocity is around 2 km/s. For such a mission, Fig. 12 shows how the various architectures would perform in terms of propulsion system mass fraction, but also dry mass fraction. For the scenario, the required RCS system ΔV was 5 % of the overall budget, leaving the remaining 95 % to the ME operation.

Fig. 13 shows how sensitive the performance comparison is to RCS allocated ΔV budget. It has been analysed the effect of increasing this requirement to 25 % of the overall budget. The effects of the

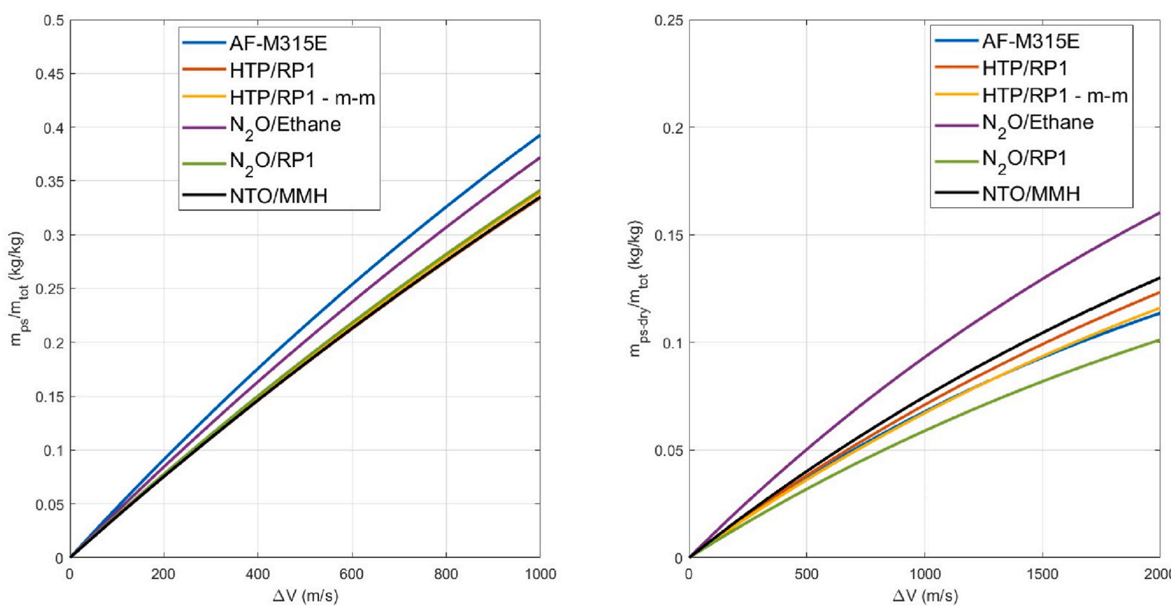

Fig. 11. Comparison of all the architecture performances in terms of propulsion system mass fraction and dry mass.

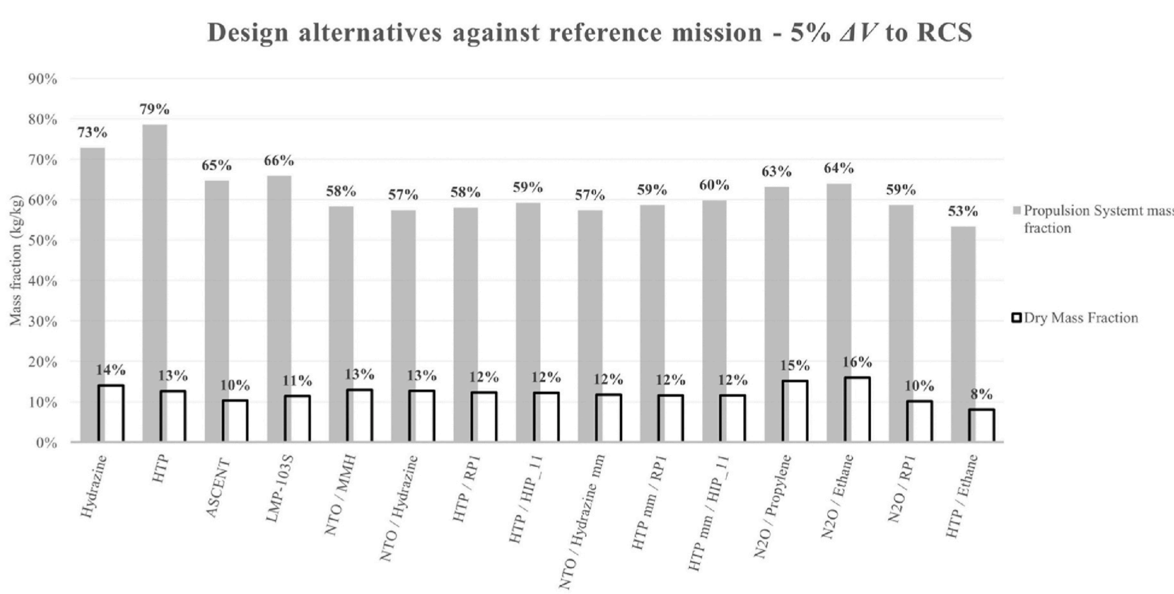

Fig. 12. Performance comparison against a reference scenario of 2 km/s ΔV with 5 % of the budget destined to RCS.

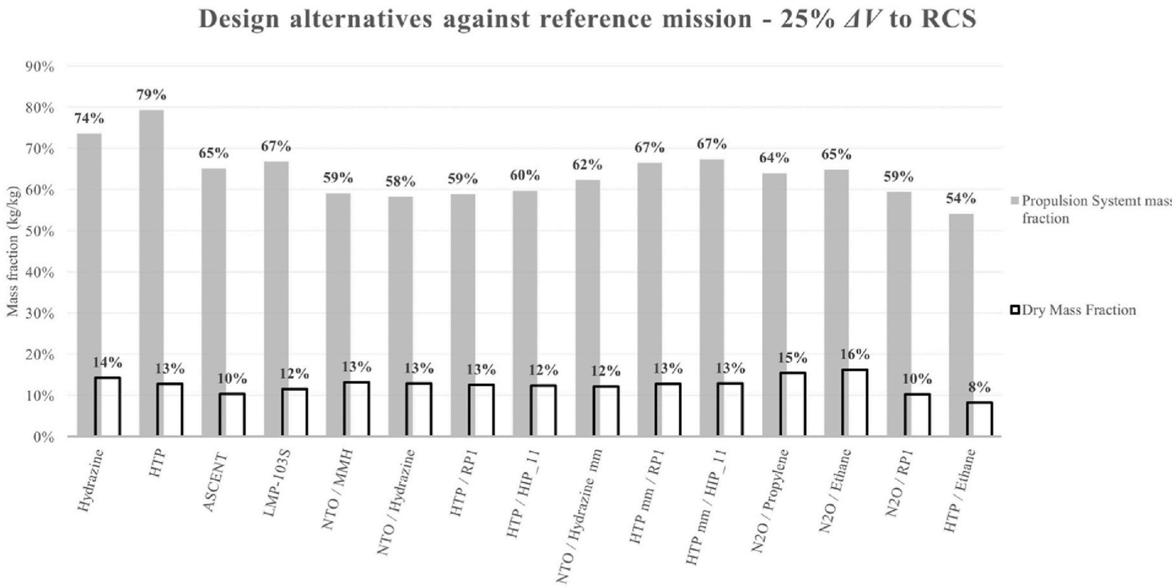

Fig. 13. Performance comparison against a reference scenario of 2 km/s ΔV with 25 % of the budget destined to RCS.

requirement change are, as expected, minimal on the dry mass, but more notable on the wet mass. The operation of RCS has now a more notable impact, and its lower performance cause a general decrease of mass efficiency. It is observable also a light improvement in dry mass of some options such as the multimode architecture, where the higher request of HTP, that has a higher density than RP1, made the system need less tank mass.

Finally, the potential addition of proximity manoeuvres sub-systems has been discussed for the various alternatives but not included in the overall performance comparison. The presence of such system is considered an added option, and the RCS could perform itself this function, depending on the capabilities of the thrusters, the overall system size and requirements compatibility. Some options, especially those with monopropellant engines on board, present easier scalability of the technologies in terms of simplicity and appear more adaptable to such requirements. However, all the other options could theoretically develop similar capabilities with dedicated effort.

4.7. Future steps

The analyses shown in the study are based on a limited number of assumptions to standardize the comparison of different alternatives, that however could assume a different and more relevant importance in real-life scenarios. The study gives the necessary information and assumptions to perform preliminary selection of system architectures without excessive complexities. Future work will focus on adding details to the comparison, even though it will result in increased complexity. The areas where more details are needed to make the comparison more accurate focus on the utilization of more detailed mission analyses to extrapolate precise requirements and on the methods to calculate the various inert mass fractions.

The study of a detailed mission analysis allows to analyse the relevance of ΔV budget allocated to RCS more in detail than in the previous section, and the necessity of additional thrusters for proximity manoeuvres, feature only partially considered in the comparison. The thrust level of the various RCS and ME was not set and could have significant repercussions on the system design, including the number of thruster elements, components, and fluidic lines.

Future crucial work is needed to add details to the various mass fractions estimations, as major assumptions were made during their calculation. For the tankage and pressurization system mass fractions calculation, analytical relationships have been obtained. These relationships are a mere simplification of components design and manufacturing and cannot capture the overall complexity of them. Different propellants have numerous materials compatibility issues, and, in the field, there is a growing interest in carbon fibre tanks that are much lighter than analysed components. The finalized tanks for the various options could result in being very different from each other, while during the performed comparison, a standardized option has been utilized.

In conclusions, additional details can be a valuable contribution to the comparison that can be extracted by real-life missions or detailed studies. The dedicated mission analysis considerations are doubtlessly extremely useful to provide further insights into requirements for the various propulsion systems design options possibly neglected in the present comparison.

5. Conclusions

The wide set of missions and capabilities comprised in the wide umbrella of on-orbit servicing include concepts that are still being developed. Many companies are now trying to develop OTVs for wide availability, trying to capture a share of the growing market. These new developments could represent the future of the space economy, evolving into missions not yet conceptualized.

Within the new design of such systems, novel propellants, less toxic than historical options, can cover an important role, providing advantages in terms of ground operations simplification and preparation. These propellants are usually referred to as *green* propellants, although there is not a clear definition of it.

The compounds, that are quickly becoming widespread, have the potential to bring advancements in overall capabilities on top of reduce the complexity of ground operations. The study outlined and compared the prevalent of the many design choices that involve new and old propellants and related technologies. The analysis utilized simplified architectures to compare the various options between each other and provided all the information to perform successive, more extensive, dedicated studies. Determining the optimal architecture for a specific mission involves intricate trade-offs that necessitate further consideration of additional parameters, not considered in the present analysis. Dedicated studies should include a deeper evaluation of the system's intended capabilities during its entire lifecycle, and how the various options could impact them. However, during preliminary design phases, the analyses in this study provide the necessary information to perform initial evaluations that need to be successively improved to include more detailed mission requirements and the various components composing the architectures.

Nevertheless, from the study it is evident that some green propellants-based alternatives are, at the very least, comparable with hydrazine-based designs in terms of performance. Instead of focusing on the sole specific impulse, commonly utilized to compare propulsion systems, the study used the system specific impulse to compare various options. The system specific impulse comprises the effects of the propellants physical properties and is more precise to draw conclusions, at least at a preliminary phase.

The analysis shows how architectures based on novel propellants can often capitalize on synergies that result in significant system complexity reduction. In particular, two alternatives appear promising in terms of both performance and complexity reduction.

- Architectures based on multi-mode exploitation of hydrogen peroxide promise to reduce the complexity of systems, leaving performances almost unaltered with relatively minor re-designs of existing systems.
- The utilization of self-pressurized propellants can enable systems without external pressurization elements. These systems are not as performant as other options because the propellants are less dense than other alternatives, nonetheless there is space for innovation using such compounds. In particular, within the framework of the study, the utilization of self-pressurized compounds as a pressurizer for both propellants, referred to as the single tank self-pressurizing option, has shown the highest efficiency in terms of mass. The system has, however, never been tested and needs further developments and considerations before being ready to be applied to future OTVs.

Foreseeably, as the number of new entrants in the space sector continues to increase, and in view of the possible advantages described in the study, there is a likelihood of more ventures adopting green propellants and related technologies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.actaastro.2024.01.032.

Appendix A

The following section describes the procedure utilized to obtain the tankage fractions. The definitions apply.

m_T	= mass of tank
m_P	= mass of stored propellant
m_G	= mass of pressurizing gas
P	= storage pressure
S_F	= Safety factor
r	= radius of tank
L	= cylindrical length of tank
ρ_w	= density of tank material
σ_w	= ultimate strength of tank material

A cylindrical tank mass can be calculated as Eq. (A.1):

$$m_T = S_F 2\pi r^3 \left(1 + \frac{L}{r}\right) \frac{\rho_w}{\sigma_w} \bullet \mathrm{P} \tag{A.1}$$

While the ccontained propellant average mass can be expressed as Eq. (A.2):

$$m_P = \mathrm{V_P}\rho_{\mathrm{avg}} = \pi \mathrm{r}^3 \left(\frac{4}{3} + \frac{\mathrm{L}}{\mathrm{r}}\right)\rho_{\mathrm{avg}} \tag{A.2}$$

The deriving tank fraction can be written as Eq. (A.3):

$$f_t = \frac{\mathrm{m_T}}{\mathrm{m_P}} = \mathrm{S_F}\frac{3(1 + \mathrm{L/r})}{2\left(1 + \frac{3}{4}\frac{\mathrm{L}}{\mathrm{r}}\right)} \frac{\rho_w}{\sigma_w} \frac{\mathrm{P}}{\rho_{\mathrm{avg}}} = \frac{\mathrm{K}}{\rho_{avg}} \tag{A.3}$$

The parameter K depends on the operating pressure, safety factor and material selected. Table A1 summarizes the calculations performed for some of relevant materials. Calculations performed for a Maximum Expected Operating Pressure (MEOP) of 35 bar and 65 bar, L/r of 2. The safety factor utilized is 1.5 for all materials but carbon fiber, for which it has been used a factor of 3 because the minimum thickness formula used to derive A.1 is not valid.

Table A.1
Tank calculations for common structural materials

	Density [g/cm^3]	Ultimate Strength [MPa]	K - low pressure [kg/m^3]	K - high pressure [kg/m^3]
4130 Steel	7.83	862	85	160
Titanium Ti6Al4V	4.46	950	45	82
Aluminium AA6000	2.8	413	50	90
Carbon Fiber	1.9	2500	21	38

The parameter K does not take into consideration the presence of propellant management devices nor thermal insulation, both often necessary for the correct operation of the tanks. Such devices could take up to 20 % of the overall tank mass. For the study, it has been taken the average K value between the considered materials eventually multiplied by 1.2. The selected values are 60 for the low-pressure tanks and 110 for the higher pressure. It is attached a market survey of a selected group of available off-the-shelf components in Figure A.1. The utilized values are in the conservative range, justifying the neglection of the mass related to the presence of surface tension equipment and diaphragms.

The calculation is analogous for pressurizing gas tanks, for which the storage pressure is 200 bar and the mass of gas is calculated in order to guarantee 25 bar in the main tanks, as per Eq. (A.4).

$$f_{PressSyst} = \frac{m_{PressSyst}}{m_P} = \frac{m_{T-G} + m_G}{m_P} = = \frac{m_G \bullet \left(\frac{m_T}{m_G} + 1\right)}{m_P} = \frac{\rho_{G@25bar} \bullet \left(\frac{K}{\rho_{G@200bar}} + 1\right)}{\rho_{avg}} \tag{A.4}$$

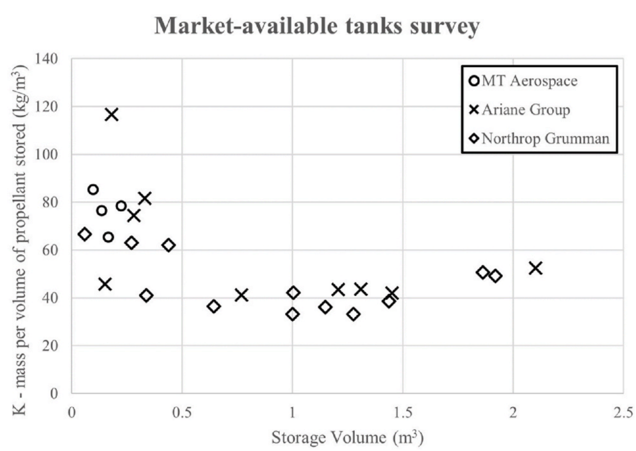

Fig. A.1. Tanks available in the market survey, mass of tank dry mass per storable volume [39,40]

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