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ORIGINAL ARTICLE

# Challenges and Opportunities of Green Propellants and Electric Pump Feeding for Future European Kick Stages

**L. Ordonez Valles[1,3] · L. Blondel Canepari[2] · U. Apel[1] · M. Tajmar[3] · A. Pasini[2]**

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## Abstract

This paper analyses the synergy between two innovative technologies: green propellants and electric pump feeding, for a 500 N engine thrust range. The novel approach is then compared to the legacy configuration, i.e., an MMH/NTO pressure fed system. First, a discussion of the benefits and challenges of the different technologies is presented. Subsequently, the proposed configuration relying on green propellants and e-pumps is investigated. After selecting hydrogen peroxide as the baseline oxidiser, a comparative analysis of different fuel candidates is conducted, leading to the selection of propane as fuel. Furthermore, the second part of the paper weights the novel configuration against the standard one and confronts their propulsive performance and mass budget. Results show that the implementation of electric pump feeding can leverage the performance of the selected green propellant outpacing the conventional solution.

**Keywords** Electric-pump-fed · Green propellant combination · Kick stage configuration

### Abbreviations

| | |
|---|---|
| ASCenSIon | Advancing space access capabilities—reusability and multiple satellite injection |
| EIL | Energetic ionic liquids |
| EPF | Electric pump feeding |
| GHS | Global harmonized system |
| GP | Green propellants |
| HTP | High-test peroxide |
| LEO | Low earth orbit |
| LH2 | Liquid hydrogen |
| LOx | Liquid oxygen |
| LRE | Liquid rocket engine |
| MMH | Monomethyl hydrazine |
| NTO | Nitrogen tetroxide |
| OFAT | One factor at a time |
| SRM | Solid rocket motors |
| UDMH | Unsymmetrical dimethyl hydrazine |

### List of symbols

| | |
|---|---|
| $H_2O_2$ | Hydrogen peroxide |
| $I_{sp}$ | (Mass) specific impulse [s] |
| $N_2H_4$ | Hydrazine |
| O/F | Oxidizer-to-fuel ratio |
| $m_0$ | Initial pressurant mass [kg] |
| $p_g$ | Instantaneous pressurant pressure [Pa] |
| $V_0$ | Initial pressurant volume [$m^3$] |
| $P_p$ | Propellant tank pressure [Pa] |
| $V_p$ | Propellant tank volume [$m^3$] |
| $K$ | Adiabatic coefficient |
| $R$ | Specific gas constant [J/kg K] |
| $T_0$ | Initial pressurant temperature [K] |

## 1 Introduction

Traditionally, the pressurisation of propellants for space applications is performed by implementing either pressure-fed or turbopump systems.

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✉ L. Ordonez Valles
livia.ordonjez-valles@hs-bremen.de

L. Blondel Canepari
lily.blondel@ing.unipi.it

U. Apel
uapel@fbm.hs-bremen.de

M. Tajmar
martin.tajmar@tu-dresden.de

A. Pasini
angelo.pasini@unipi.it

[1] Hochschule Bremen, Neustadtswall 30, 28199 Bremen, Germany

[2] Università di Pisa, 8 Via Gerolamo Caruso, 56122 Pisa, Italy

[3] Institute of Aerospace Engineering, Technische Universität Dresden, 01062 Dresden, Germany

In the first case, propellants are stored at high pressure in the tanks and then directly fed into the combustion chamber. Due to its inherent simplicity, this option is the standard choice for small to medium thrust applications [1].

On the other hand, turbopumps are essential to cope with the required chamber pressures of high thrust applications, such as in the case of first or boost launcher stages [2].

The substitution of the turbine with an electric motor, i.e., electric pump feeding, can become a game-changing solution for particular applications, since, on one side, it can comparatively increase the performance with respect to pressure fed systems and, on the other side, reduce the complexity with respect to turbopumps. However, the challenge still lies in minimising the mass, especially the battery mass, when a significant amount of power is required [3–6]. Hence, the success of this technology is deeply linked to battery development. As this last evolves, so does the appeal of electric pump feeding, and with it, the necessity to deliver an update on the technology's feasibility.

Research on electric pump feeding started in the eighties. A few decades later, namely, in the early 2000s, there was a renewed interest in the topic mostly driven by the rapid improvements in battery and electric motor technology led by the automotive industry [7]. Worthwhile from this period is the research of Tacca, Lentini and Rachov regarding the comparison of electric pump feeding with pressure fed systems and gas generators. Their work presented a mass model to compare these different types of pressurisation means [5, 8].

Some years later, in 2018, Kwak et Al. applied this methodology to estimate the masses of a LOX/Kerosene electric pump-fed system and its gas generator version [4].

Alternatively, the implementation of electric pump-fed technology has also been examined for hybrid propulsion. Ref. [9] presents a study to develop an electrically driven oxidiser pump for a Vega type launcher.

More recently, Ref. [3, 10] focused on the applicability of electric pump feeding in the low thrust range. Ref. [10] assessed the influence of the mixture ratio on the performance of a LOx/Methane electric pump-fed engine. On the other side, Ref. [3] studies the development of a 500 N LOx/RP-1 electric fed system and compares its performance to its gas generator counterpart.

Nevertheless, from a practical standpoint, the best example of this technology can be found onboard the US-NZ RocketLab’s launcher, namely, Electron, where electric pump feeding is used to pressurise the propellants in the Rutherford engines [11].

Switching topics, replacing toxic propellants with more sustainable options can greatly benefit safety and simplicity of the space system [2, 12, 13]. The so-called “green propellants” can bring meaningful advantages thanks to their low toxicity, such as reducing the strict security and safety handling measures currently in place [13, 14]. In the long run, this promises a reduction in life-cycle costs and makes them highly attractive for future space missions [15]. However, several parameters must be considered to match the most suitable green propellant with the foreseen application. The system considered in this paper is a bipropellant storable liquid thruster. The appropriate choice of oxidiser/fuel combination is described in Sect. 3.1.

Contrarily to the latest studies in electric pump feeding mentioned above, namely, Ref. [3], the present paper will tackle the same argument but from a totally different perspective. The electric pump-fed system will be confronted with its pressure fed counterpart, since these last represent the legacy solution for propulsion systems within the examined range, i.e., hundreds of Newton thruster class [16–18]. Moreover, the use of green propellants is also an integrant part of the study. In fact, the use of electric pump feeding can leverage green propellants’ performance, helping to replace highly toxic and dangerous hydrazine while providing significant advantages in terms of sustainability, safety, and, ultimately, costs.

The paper will be structured as follows:

- Features of both technologies:

  This section will provide an overview of the perks and cons of the proposed novel technologies
- Combining both innovations: their application to the selected study case

  This section describes the followings:

  o Selected study case
  p Green propellants selection
  q System architecture
  r Methodology
  s Mass model
  t Kick stage specifications

- Results

  Results will be structures as follows:

  o Mass budgets and OFAT sensitivity analysis
  p Volume envelope
  q Electric pump-fed system power budget

- Conclusions and way forward

## 2 Features of Both Technologies

This section presents a comprehensive summary of the main features associated with both electric pump feeding and green propellants [2, 19].

## 2.1 Electric Pump Feeding

- Compared to pressure-fed, electric pump-fed systems can bring a significant dry mass reduction. Indeed, implementing electric pump feeding allows reducing the required pressure of the propellant tank and, consequently, its mass. The second significant advantage concerns the possibility of improving the propulsive performance by increasing the combustion chamber pressure with respect to the one of a pressure fed system [2, 19].

  However, the additional components, especially the battery, lead to a mass penalty compared to the simple pressure fed systems. This increase in the number of components can lead to lower reliability. Therefore, both factors represent the most important challenge to overcome for future technology implementation [2, 19].
- Compared to turbopumps, electric pump feeding can reduce the system complexity by considerably decreasing the number of components, e.g., no need for a gas generator to drive the turbine. This aspect leads to higher overall simplicity and, consequently, higher system reliability. Another relevant advantage is the improved reignitability: the ignition sequence is significantly simplified in the case of electric pump-fed systems. This last feature can trigger the number of reignitions and hence, improve satellite multi-injection capabilities [2, 19].

  In the same way as for the pressure fed comparison, the electric motor and battery masses are the main criticalities that could prevent the establishment of electric pump feeding in the market. Moreover, the battery efficiency is strongly dependent on temperature, and therefore, heavy thermal insulation may be needed to ensure its correct operation [2, 19].

Table 1 provides a summary of these main features [2, 19].

For the sake of completeness, an overview of the main components of each pressurisation system is provided in Fig. 1 [20].

**Table 1** Electric pump feeding main advantages and disadvantages

| Electric pump-fed vs pressure-fed | | Electric pump fed vs turbopumps | |
|---|---|---|---|
| Advantages | Disadvantages | Advantages | Disadvantages |
| Tank mass reduction | Additional components mass penalty | Reduction of complexity can lead to higher reliability | Battery and electric motor mass and efficiency |
| Propulsive performance improvement thanks to higher chamber pressures | Lower reliability | Improved re-ignitability | Battery and electric motor thermal control |

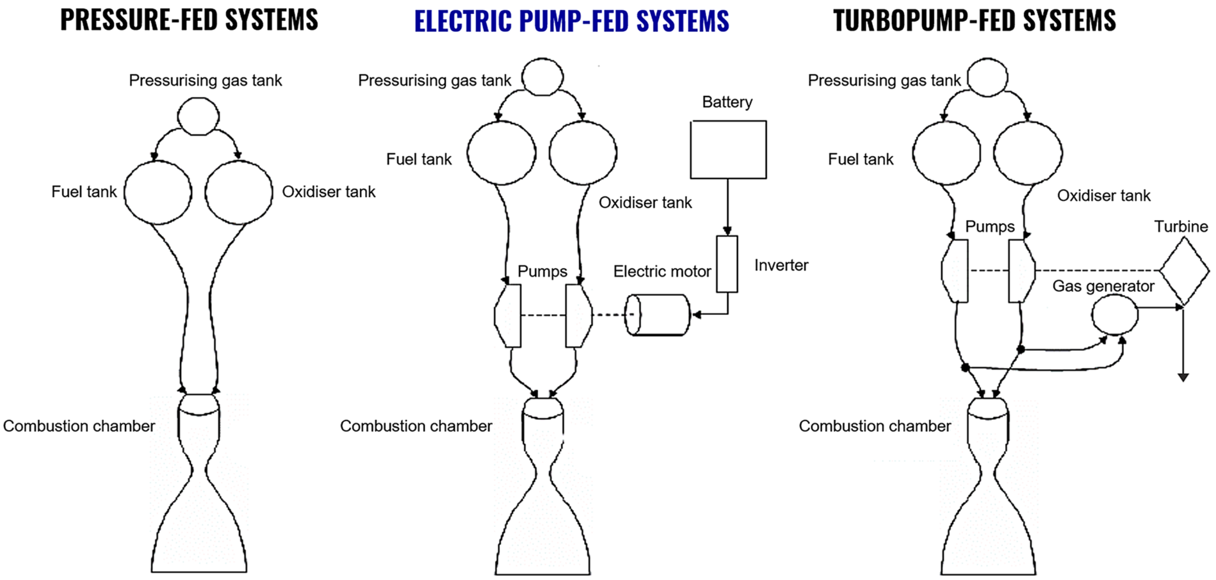


**Fig. 1** Pressurisation methods overview [20]

## 2.2 Green Propellants

The main driver for the research on green propellants is to identify a substitute for the most widely used rocket fuel in our analysed thrust range: hydrazine ($N_2H_4$) and its derivatives, namely, Unsymmetrical DiMethyl Hydrazine (UDMH) and Monomethylhydrazine (MMH) [14, 21]. Their high intrinsic toxicity and harmful potential make their handling and manipulation not only tedious but costly, as strict safety and security protocols have to be observed [13, 14]. The noxiousness of hydrazine even brought it to be added to the EU's list of Substances of Very High Concern (SVHC) in 2011 [13, 22] and to be acknowledged as a harmful compound in most countries worldwide [2, 23, 24]. While no explicit measures to ban hydrazine have been taken yet by the REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) regulation, its upcoming usage limitation is expected and will have a profound impact on the space propulsion market [25]. This setting builds a clear incentive to promote research on green propellants to identify suitable substitutes [12, 14].

As a general definition, the appellation "green propellants" refers to less-toxic compounds, storable at ambient temperature and able to provide high propulsive performances [13, 14]. While calling "green" most propellants that are not hydrazine has passed into everyday speech, the appellation in fact refers to "greener" propellants which are not exempt from safety precautions [14]. Table 2 gives a general overview of the main advantages and disadvantages of green propellants with respect to conventional ones.

To be designated as "green", a propellant is evaluated with respect to four main characteristic features: toxicity, storability, performance and cost & availability [12]:

- Standing as one of the most important factors, the different compounds toxicity can be compared using the 1:5 scale provided by the Global Harmonized System of classification and labelling of chemicals (GHS) [12, 26, 27]. As a grade of 1 goes to the most toxic species, hydrazine, with a GHS of 3, is categorised as toxic and carcinogenic [23]. To be designated as green toxicity-wise, a propellant should display a score at least one unit higher than hydrazine, i.e., equal to or higher than 4 [12]. Note that the most used derivatives of hydrazine, MMH and UDMH, display a GHS score of 2 [22]. The acute toxicity of chemicals is evaluated with respect to different sections, namely, [27]:

- ▪ Oral
- ▪ Dermal
- ▪ Gases
- ▪ Vapours
- ▪ Dust & mists

In addition to the acute toxicity, other hazards are regarded when establishing the safety sheet of a compound [14]. While the GHS final score is useful for comparing chemicals against each other, a more detailed look at the different categories should be observed to validate future fuels for their foreseen applications. Moreover, the GHS final score is currently unavailable for some compounds and is not reported in this paper.

- At the start of the research, green propellants were meant to replace storable toxic ones with the foreseen goal of reducing space access costs [13, 14]. Storable means in liquid form over the operational range [– 30 °C, 80 °C] [12]; therefore, cryogenic propellants are not considered green and are not accounted for in this study. A sub-category of "storability" includes the handling of propellants. Reduced toxicity implies easier handling. For example, if tanks could be already filled with propellants before arriving at the launch site, substantial cost savings could be made [14].
- As the research aims at substituting hydrazine with a compound offering equivalent or higher specific impulse, performance stands as a key aspect when weighting different propellants against each other [2, 12–14]. The performance is here evaluated through the mass specific impulse ($I_{sp}$); however, other parameters such as the density specific impulse and thrust chamber temperature [14] should be included in a more refined trade-off. With respect to the thrust we want for our system, the specific

**Table 2** Advantages and disadvantages of green propellants vs conventional ones

| Green vs conventional propellants | |
|---|---|
| Advantages | Disadvantages |
| – Reduced toxicity<br>– Reduced safety precautions during handling<br>– Easier storability for long-term missions<br>– No risk of obsolescence with respect to REACH<br>– Improved efficiency, reduced complexity<br>– Reduced production, transport and on-ground operations costs | – Lower maturity than hydrazine-based propellants<br>– Not many green propellants have been flight-proven and are frozen at lower TRL<br>– Reluctance from industry as long as hydrazine is authorised<br>– Face significant development cost at system and subsystem level |

impulse of the selected bi-propellant combination is used here to determine the mass of propellant needed and then the tank masses.

- Cost holds a crucial role to assess the economic viability of introducing a novel given propellant [13]. A good example here is hydrogen peroxide: up to 87.5% concentrated, the demand is high, the production process is well-established, and the compound is hence available at a low price. However, as the performance scales up almost linearly with HTP purity, higher concentrations of hydrogen peroxide result in higher $I_{sp}$. In the case of a 98% mixture, most commonly used for launcher applications [28, 29], the available price is still high as there is no well-rounded process behind its production yet. Cost is, however, not assessed here as a figure of merit of our green propellant selection.

## 3 Combining Both Innovations: Their Application to the Selected Study Case

Kick stages are fundamental to deploying multiple payloads into their operational orbits after a rideshare or a piggyback launch. Multi-injection capabilities are essential to enable new space mission requirements, such as efficient constellation deployment or the injection of payloads from different operators within a single launch. Moreover, they can also improve the space transportation versatility for GTO, lunar or deep space missions and, in the near future, provide the space market with a whole set of innovative in-orbit services.

Either well-established launcher providers or fresh startups consider including this technology in their portfolio to satisfy these new customers' demands.

Within the first category, ArianeGroup is responding by developing ASTRIS, a kick stage tailored for the new Ariane 6 launcher, whose maiden flight is expected for 2024 [29].

RocketLab offers another good example with their kick stage; in-house developed and manufactured, it is powered by the Curie engine (100 N thrust) [30].

Moreover, startups such as Rocket Factory Augsburg (RFA) also plan the development of a kick-stage to improve their business cases [31].

With these market trends in mind, this paper seeks to embrace these needs, i.e., multi injection capabilities and sustainability, by assessing the performance of our proposal: a kick stage powered by e-pumps and propelled by a green combination.

The mass budget is calculated and compared to the conventional storable Monomethylhydrazine and Nitrogen Tetroxide (MMH/NTO) combination. This data allows estimating the system dry mass and, together with the specific impulse, the wet mass. Altogether greatly influences the system $\Delta v$ capabilities, one of the key drivers for customers to select their payload carrier.

Table 3 summarises the main features of both kick stages configurations. The green propellant selection is performed in the next section.

**Table 3** Kick stage configurations

| | Kick stage configuration | |
|---|---|---|
| | Proposed system | Legacy system |
| Propellant | Green propellant combination | MMH/NTO |
| Pressurisation system | Electric pump | Pressure fed |

### 3.1 Green Propellant Selection

#### 3.1.1 Green Oxidiser Selection

The thrust level studied in this paper suggests the utilisation of a bipropellant propulsion system. The traditional choice in this thrust range goes for the well-established nitrogen tetroxide (NTO) as oxidiser and with hydrazine or one of its derivatives as the fuel. NTO has indeed been continuously used in both the URSS and the USA since the 1950s [32]. It is, however, extremely toxic and has been ranked with the lowest possible GHS score:1.

The choice among green oxidisers is limited. Indeed, the most common options are either nitrous oxide or hydrogen peroxide. A summary table of their main features is shown in Table 4.

The high vapour pressure of nitrous oxide brings an interesting self-pressurization capacity. However, since our system aims at maximizing the benefit of implementing a pump, having a high pressure in the oxidizer tank does not bring any advantage to our system and this option is, therefore, discarded.

On the other hand, hydrogen peroxide brings its maturity as a strong asset, since it has been used in space for decades [38]. It offers several advantages, such as low toxicity, high volumetric impulse and exceptional performance when combined with some hydrocarbons [12]. Its ability for multi-mode configuration also brings an additional valuable perk as it can operate in both monopropellant and bipropellant mode, providing versatility to the space system [12]. However, one of the main drawbacks of hydrogen peroxide remains its incompatibility with common tank materials, namely, Titanium [12]. Unstable compound hydrogen peroxide needs to be used with suitable materials to avoid self-decomposition, especially when looking at the long-term missions foreseen in the near future. Even with a suitable material identified, special handling is required to avoid the risk of over-pressurised gas in the vessel and, in the worst

**Table 4** Pros and cons of the different storable liquid oxidisers

| | Green vs conventional oxidisers | |
|---|---|---|
| | Advantages | Disadvantages |
| Nitrogen Tetroxide (NTO) | – High specific impulse in biprops mode with hydrazine derivatives [33]<br>– Well-established technology [34]<br>– Cheap & available [34] | – Extremely toxic [22]<br>– Stringent & costly fueling operations [14, 35] |
| Nitrous Oxide ($N_2O$) | – Low cost [12]<br>– Non-toxic [12]<br>– Self-pressurization capability [12] | – Extremely high combustion temperature [12]<br>– Low density [12]<br>– Low performance [12] |
| Hydrogen Peroxide ($H_2O_2$) | – High maturity [36]<br>– High performance in bipropellant mode [12]<br>– Dual-mode system (oxidiser in biprops, pure in monoprop) [13] | – Material compatibility [13]<br>– Low performance in monopropellant mode [12]<br>– High decomposition rate [37]<br>– Careful handling protocol [13] |

case, explosions [36]. Bearing all this in mind, 98% HTP has been selected as the baseline oxidiser for our configuration. Indeed, as the performance, i.e., the $I_{sp}$, scales up with the concentration of HTP, we chose the highest commercially available concentration.

Once the oxidiser is selected, an exploratory trade-off is realised to identify the most suitable fuel to be used in combination with 98% HTP for our case study. The result of the trade-off is reported in the next section.

### 3.1.2 Green Fuel Selection

To optimise the use of hydrogen peroxide, several hydrocarbon compounds are considered as potential fuel candidates for our study:

- Ethane
- Propene
- Propane
- Methanol
- Methane
- Butane
- RP-1

Methane is included only for comparison purposes as its necessity of being stored at cryogenic conditions does not qualify it as a green propellant according to the storability requirement presented in this paper. Not being a hydrocarbon compound, ammonia is reported as well only for comparison purposes.

As introduced in Sect. 2, green propellants are generally considered with respect to the following four categories: toxicity, storability, performance and cost & availability [12]. Among them, this trade-off focuses on the following figures:

- Toxicity/danger
- Storability
- Performance

A complete description of each fuel candidate with respect to the considered figures of merit is provided in Table 5

In the first place, the green fuel should display a significantly reduced toxicity level with respect to hydrazine. This fact is verified for almost all the fuel candidates reported here. Indeed, the carcinogenic and skin-sensitising properties of hydrazine [22] are avoided, except for Methanol. However, hydrocarbon fuels still require careful handling, since they are especially flammable and show some risk of explosions if heated. With respect to this category, propene and propane seem to be less dangerous.

In a second place, the green fuel should display good storability properties, namely, a high density and a low vapour pressure. The low vapour pressure criteria is crucial for our study, since we are trying to maximize the direct benefit of using a pump, i.e., lighter tanks with respect to a pressure-fed system. Lower tank pressures can be achieved if the stored compounds' vapour pressure is low enough, and thanks to it, lead to lighter tanks.

Bearing this in mind, an arbitrary limit of 10 bars for the vapour pressure at 25 °C has been set for our fuel candidate. Therefore, all the species displaying a dot above the red-limit-line of Fig. 2 are discarded, namely: ethane, propene and ammonia (as shown in the recapitulative Table 6).

Finally, the green fuel, in combination with 98%-HTP, shall display higher performance than the conventional MMH/NTO system. With the parameters reported in Table 7, the $I_{sp}$ of the legacy system, computed with RPA [39], is 322 s.

Table 5 reports the 98%-HTP/Hydrocarbon $I_{sp}$ values, while in Fig. 3, the same values are normalised with respect to the legacy system $I_{sp}$. With a value lower than one in

**Table 5** Properties of the green fuel candidates

| | | Ethane ($C_2H_6$) | Propene ($C_3H_6$) | Propane ($C_3H_8$) | Methanol ($CH_3$–OH) | Methane ($CH_4$) | Butane ($C_4H_{10}$) | Ammonia ($NH_3$) | Kerosene (RP-1) |
|---|---|---|---|---|---|---|---|---|---|
| Toxicity/danger | | – Extremely flammable gas<br>- May explode if heated [22] | Extremely flammable gas [22] | Extremely flammable gas [22] | – Highly flammable liquid & vapor<br>– Toxic (carcinogenic) [22] | – Extremely flammable gas<br>– Damage fertility and/or pregnancy [22] | – Extremely flammable gas<br>– May explode if heated [22] | N.A | – Flammable liquid & vapor<br>– Damage fertility and/or pregnancy<br>– Cause irritation [22] |
| Storability | $\rho$ [g.cm$^{-3}$] at 25 °C | 0.32 [37] | 0.50 [37] | 0.50 [37] | 0.79 [37] | N.A | 0.57 [37] | 0.60 [37] | 0.80 [38] |
| | $P_{vap}$ [bar] at 25 °C | 41.8 [37] | 11.5 [37] | 9.5 [37] | 0.17 [37] | N.A | 2.4 [37] | 10 [37] | 0.10 [37] |
| Performance: $I_{sp}$ [s] | | 327 [39] | 328 [39] | 326 [39] | 314 [39] | 327 [39] | 325 [39] | 310 [39] | 324 [39] |

Fig. 3, i.e., with an $I_{sp}$ lower than the MMH/NTO system, Methanol and Ammonia are excluded from the fuel candidates list, as shown in Table 6. Most of the 98%-HTP/fuel combinations show a higher $I_{sp}$ than the legacy one (i.e., are above the red line in Fig. 3).

With respect to our two destructive trade-off criteria involving vapour pressure limit and performance, only three fuel candidates are still considered at this stage: Propane, Butane and Kerosene. The first row of Table 5 shows that, with respect to toxicity/danger, propane seems the safest compound to use. Moreover, it displays a slightly higher $I_{sp}$, when combined with 98%-HTP, than Butane or RP-1. In addition to these considerations, Propane ($C_3H_8$) is a lighter, and, therefore, simpler, hydrocarbon than Butane ($C_4H_{10}$) or Kerosene ($C_{12}H_{26}$–$C_{15}H_{32}$). Therefore, higher performance and lighter hydrocarbon chain (hence

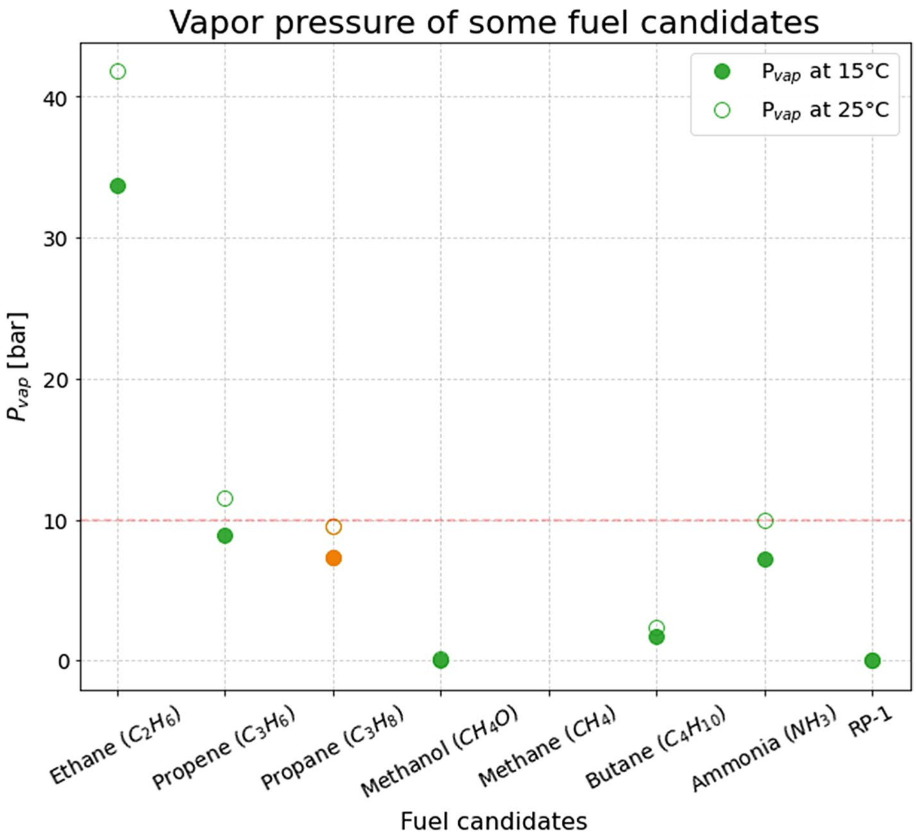


**Fig. 2** Vapour pressure of the different fuel candidates

**Table 6** Fuel trade-off destructive criteria

| | Ethane ($C_2H_6$) | Propene ($C_3H_6$) | Propane ($C_3H_8$) | Methanol ($CH_3$–OH) | Methane ($CH_4$) | Butane ($C_4H_{10}$) | Ammonia ($NH_3$) | Kerosene (RP-1) |
|---|---|---|---|---|---|---|---|---|
| Vapour Pressure below 10 bars at 25 °C | | | X | X | N.A | X | | X |
| Higher Isp than the legacy system | X | X | X | | X | X | | X |

**Table 7** Kick stage specifications

| | Kick stage | |
|---|---|---|
| | Proposed system | Legacy system |
| Thrust | 500 N | |
| Burning time | 1000 s | |
| Total impulse | 500 kNs | |
| Chamber pressure | 30 bar | 10 bar |
| Mixture ratio | 7 | 1.65 |
| Expansion ratio | 300 | |

simpler chemical decomposition reaction) have been the final drivers to select propane as the fuel for our case study. However, the much lower vapour pressure of Butane makes it a very promising alternative fuel to consider.

### 3.2 System Architecture

Figure 4 depicts a simplified architecture of the proposed kick stage, which aims to provide a functional description of the proposed kick stage propulsive subsystem. It is not intended to represent the subsystem's overall design, piping or instrumentation but to give a glimpse of the proposed subsystem functional architecture (Fig. 4).

- Storage subsystem

  Helium has been chosen as the default pressurising gas and shall be stored in a spherical tank at ambient temperature and 300 bar pressure.

  Regarding the propellant tanks, several remarks need to be considered. As later discussed in Sect. 4.1, propane displays a vapour pressure of approximately 7 bars at 15 °C. Therefore, the propane tank pressure is set to 8.5 bars to avoid propellant management-related issues, such as cavitation. Moreover, material compatibility with hydrogen peroxide is also a concern to bear in mind. Selecting a fully compatible material is critical to ensure a low HTP decomposition rate. 5254 aluminum alloy is compliant with this requirement and, hence, has been selected as the baseline material for both tanks.
- Feeding subsystem

  The feeding subsystem comprises the pumps that deliver the required heads to the propellants, the electric motors that drive the pumps, and several battery packs to power them.
- Catalytic bed

  Prior to its injection in the main combustion chamber, hydrogen peroxide is catalytically decomposed into a hot stream of water and oxygen. When used in monopropellant mode, it provides the reaction control system with the required thrust. This versatility is one of the major strengths that can settle hydrogen peroxide as the "golden" green oxidiser.
- Main combustion chamber

  Hydrogen peroxide is injected together with propane into the main combustion chamber. Due to the high combustion temperatures of the exhaust gases, cooling shall be foreseen.

### 3.3 Inputs and Methodology

The following analysis is based on the fundamental hypothesis that both systems shall deliver the same total impulse. To meet this specification, the required thrust is set to 500 N and the burning time to 1000 s. System characteristics such as specific impulses, oxidiser and fuel mass flow rates are obtained through simulation with the Rocket Propulsion Analysis—RPA tool [39].

The values of each operational parameter are presented in Table 7.

Results from RPA are reported in Table 8. The simulations were run by assuming frozen flow and default RPA reaction, nozzle and overall efficiencies.

Instead, the pressurisation system mass is obtained by developing a Matlab algorithm. This model is based on the one proposed in [20] and has been properly adapted to our purposes. After providing the total impulse and propellant mass flow rates as initial inputs, the masses of the

**Fig. 3** $I_{sp}$ of the different 98%-HTP/fuel combinations normalized by the legacy one (MMH/NTO, $I_{sp} = 322$ s)

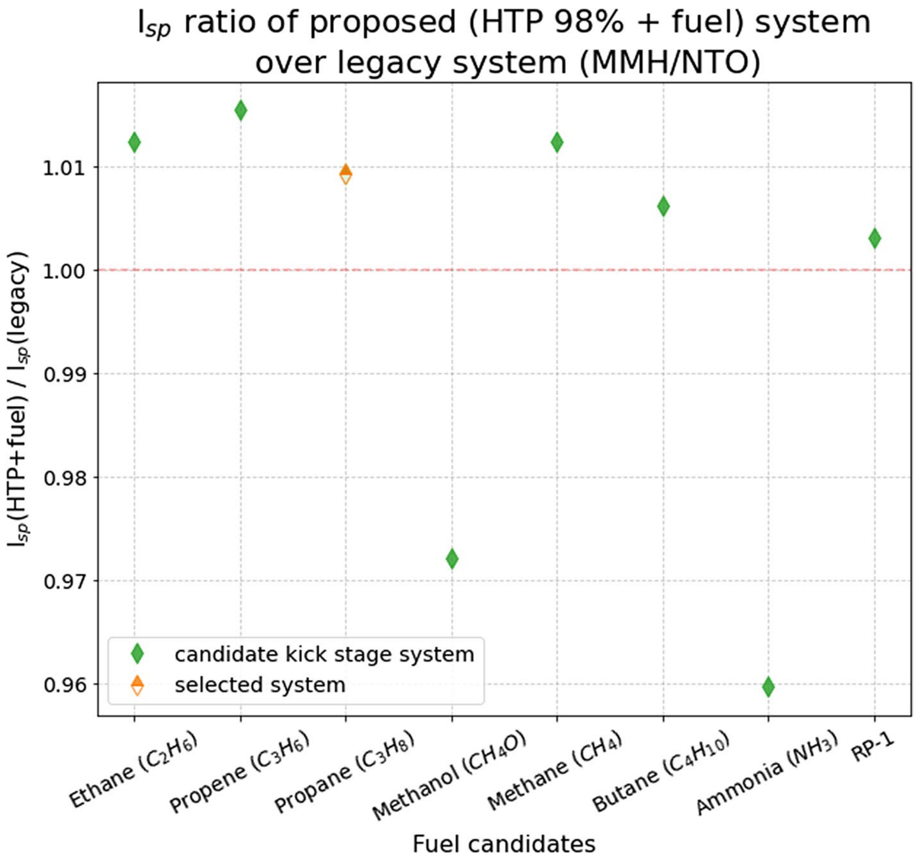
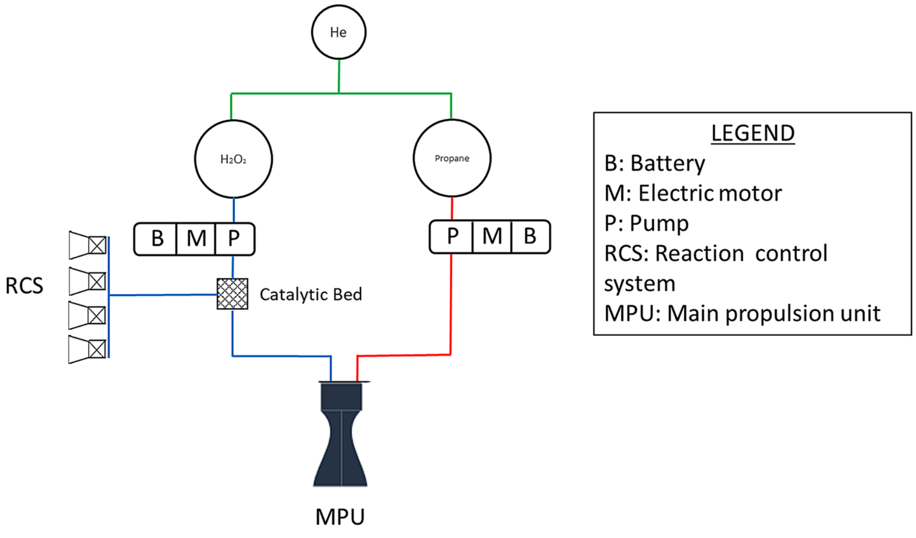


**Fig. 4** Kick stage system architecture



components shown in the equation below can be easily retrieved thanks to their modelisation in Matlab:

$$m_{\text{pressure - fed}} = m_{\text{pressurising gas}} + m_{\text{pressuring gas tank}} + m_{\text{oxidiser tank}} + m_{\text{fuel tank}},$$

$$m_{\text{electric - fed}} = m_{\text{pressurising gas}} + m_{\text{pressuring gas tank}} + m_{\text{oxidiser tank}} + m_{\text{fuel tank}} + m_{\text{fuel pump}} + m_{\text{oxidiser pump}} + m_{\text{electric motor}} + m_{\text{inverter}} + m_{\text{battery}},$$

Other secondary masses such as valves, piping or electronics are considered negligible and not included in the analysis.

### 3.4 Mass Model

- Pressurising gas mass
  Based on the conservation equation and assuming adiabatic conditions, a simplified pressurant gas mass can be computed for storable propellants [40].
- Tank masses
  The tank masses are calculated by assuming spherical tanks and Laplace's law for pressure vessels under internal pressure [41].
- Electric pump feeding components
  In addition, electric pump-fed systems shall account for the mass of the oxidiser and fuel pumps together with the electrical components required to drive them, i.e., electric motors, inverters or controllers and batteries. These masses are estimated by assuming certain power densities and, in the case of the battery, also a specific energy density. Battery mass is restrained by both power and energy density, and the selected value will correspond to the maximum of both [5].

Power densities, [W/kg], are defined as the ratio of the output power over the component mass:

$$m = \frac{P}{\delta_p},$$

Table 8 RPA results

| | Kick stage | |
|---|---|---|
| | Proposed system | Legacy system |
| Specific impulse | 326 s | 322 s |
| Mass flow rate | 0.16 kg/s | 0.16 kg/s |
| Oxidiser mass flow rate | 0.14 kg/s | 0.1 kg/s |
| Fuel mass flow rate | 0.02 kg/s | 0.06 kg/s |

where $P$[W] stands for output power, while $\delta_p$ corresponds to the power density.

On the other hand, when considering energy density, [Wh/kg], mass is expressed by

$$m = \frac{Pt_b}{\delta_e},$$

where $t_b$ represents the burning time and $\delta_e$ the battery energy density.

Moreover, the different component efficiencies for the pumps, electric motor, inverter and battery were also taken into account for computing the required powers and masses [4].

### 3.5 Kick Stage Specifications

In accordance with Sect. 3, the input parameters reported in Table 9 were selected as the reference for our use case.

## 4 Results

### 4.1 Mass Budgets and OFAT Sensitivity Analysis

Computations lead to the following masses:

Results in Table 10 show a decrease in dry mass when shifting from the more conventional pressure fed to the electric pump-fed system. The reason for this lies in the fact that, despite the additional inert mass, electric pump feeding provides a considerable reduction in tank weight and Helium savings due to the decrease in the propellant tank pressure. A detailed breakdown of the different masses is depicted in Table 11 to exemplify this reduction.

Regarding the wet mass, electric pump feeding also proves beneficial against the legacy system. The superior specific impulse (326 s vs 322 s) together with the lower dry mass are the reasons behind this difference. This reduction would translate into a payload maximisation, which at the same time, would lead to an increase in competitiveness and, ultimately, in profits.

Moreover, the system would enjoy the intrinsic advantages of using green propellants.

On the other hand, it can also be argued that the mass differences are not conclusive enough to definitely establish a clear advantage of the proposed system over the legacy one. When moving to a more detailed design, and hence considering more accurate components masses, such as valves, the thruster masses or cooling, the legacy system may eventually surpass our proposal. Although this possibility cannot be discarded, the available data is not complete enough to drop any conclusion. Moreover, while

**Table 9** Kick stage input parameters

| | Kick stage configuration | | |
|---|---|---|---|
| | Proposed system | Legacy system | Comments |
| Pressurant species | He | He | |
| Pressurant tank pressure (bar) | 300 | 300 | |
| Pressurant tank material | Al alloy | Al alloy | |
| Tank thickness FoS | 2.5 | 2.5 | |
| Geometry | Spherical | Spherical | |
| He mass uncertainty factor | 30% | 30% | |
| Fuel tank pressures (bar) | 8.5 | 13.5 | |
| Oxidiser tank pressures (bar) | 3 | 13.5 | |
| Ullage | 5% | 5% | |
| Mass residuals | 5% | 5% | |
| Propellant tank material | Al5254 | Al7050 | Hydrogen peroxide compatible material [42] |
| Tank thickness FoS | 2.5 | 2.5 | |
| Geometry | Spherical | Spherical | |
| Pump efficiency | 0.4 | NA | Conservative hypothesis Significantly lowered down from literature [3–5, 7] |
| Electric motor efficiency | 0.8 | NA | Conservative hypothesis [3–5, 7] |
| Inverter efficiency | 0.9 | NA | In line with literature figures of merit [3–5, 7] |
| Battery cell efficiency | 0.9 | NA | In line with literature when considered [3–5, 7] |
| Pump power density (kW/kg) | 1.25 | NA | Conservative hypothesis Significantly lowered down from literature [3–5, 7] |
| Electric motor power density (kW/kg) | 3.8 | NA | BLDC electric motor<br>In line with literature figures of merit [3–5, 7] |
| Inverter power density (kW/kg) | 60 | NA | In line with literature figures of merit [3–5, 7] |
| Battery power density (kW/kg) | 3 | NA | Li–Po battery type<br>In line with literature figures of merit [3–5, 7] |
| Battery energy density (Wh/kg) | 180 | NA | Li–Po battery type<br>In line with literature figures of merit [3–5, 7] |
| Dry mass margin | 10% | 10% | For accounting, other inert masses, such as piping, valves or electronics |

pressure-fed systems powered by MMH/NTO are well-known and have been optimised for their typical use-case over time, this has not happened for the novel electric fed systems yet.

Nevertheless, to clarify this last statement, a one factor at a time (OFAT) sensitivity analysis was carried out to investigate the uncertainties of certain parameters and their effect on the total computed system dry mass.

The parameters that were defined as worth to be investigated are the ones related to the novel electric pump feeding configuration, i.e., pump, electric motor and batteries figures of merit. The lack of available data regarding hydrogen peroxide and propane electric pump-fed components for this operational range introduces a degree of uncertainty in the results, these last being investigated via this sensitivity analysis.

**Table 10** Kick stage mass results

| | Kick stage configuration | | |
|---|---|---|---|
| | Proposed system (kg) | Legacy system (kg) | Percentage mass saving with respect to legacy system |
| Pressurisation system dry mass | 17.4 | 19.2 | 9.4% |
| Pressurisation system wet mass | 179.6 | 185.1 | 3% |

**Table 11** Kick stage pressurisation system mass budget

| | Kick stage configuration | |
|---|---|---|
| | Proposed system (kg) | Legacy system (kg) |
| Pressurising gas | 0.4 | 0.77 |
| Pressuring gas tank | 7 | 12.3 |
| Fuel tank | 1.6 | 1.2 |
| Oxidiser tank | 2.8 | 3.2 |
| Pump | 0.9 | NA |
| Electric motor + Inverter | 0.3 | NA |
| Battery | 2.7 | NA |
| Miscellaneous | 1.7 | 1.7 |
| Propellant | 163.8 | 165.9 |

Hence, the studied parameters are the following:

Pump

- Pump efficiency ($\eta_p$)
- Pump power density ($\delta_p$)

Electric motor

- Electric motor efficiency ($\eta_{em}$)
- Electric motor power density ($\delta_{em}$)

Battery

- Battery power density ($\delta_b$)
- Battery energy density ($\delta_e$)

In addition, the variability range was decided to be ± 25% with respect to the nominal values. The selected uncertainties were implemented in the mass model, and their effect was then quantified in the form of percentages with respect to the nominal system dry mass via this sensitivity analysis.

The results are presented in the form of a tornado chart, where the impact of changing one a time the aforementioned variables is shown from most to less relevant order (Fig. 5).

Columns in blue represent the percentage of increase in system dry mass when input variables are reduced by − 25%. Contrarily, columns in orange represent the decrease in dry mass due to the correspondent + 25% increase.

As can be derived from the figure, the pump efficiency is the value that most influences the computed final dry mass, while the battery power density does not. The reason lies in the fact that the system's battery mass is energy density constrained.

The final conclusion retrieved is that by decreasing a 25% any of the electric pump fed input parameters, the mass of this system remains lower than the pressure fed case. For simplicity, the green dotted line in the graph displays the correspondent pressure fed system dry mass, i.e., 19.2 kg and 10.3% more than its electric pump-fed counterpart.

Finally, it is important to note that, as described in Sect. 3.5., the assumed values were already conservative when compared to the ones presented in literature.

For the shake of completeness, the actual inputs and dry masses values are presented in Tables 12 and 13:

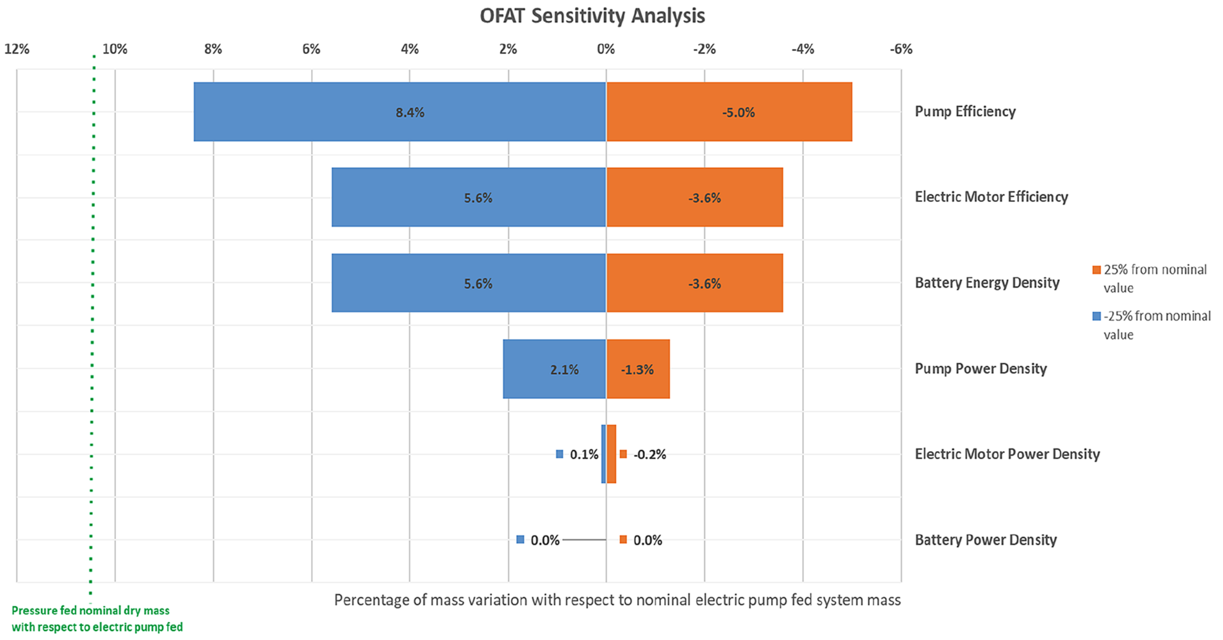


**Fig. 5** OFAT sensitivity analysis

**Table 12** OFAT sensitivity analysis input values

| | Input parameters | | | |
|---|---|---|---|---|
| | Units | − 25% | 0 | +25% |
| Pump efficiency ($\eta_p$) | – | 0.3 | 0.4 | 0.5 |
| Electric motor efficiency ($\eta_{em}$) | – | 0.6 | 0.8 | 1 |
| Pump power density ($\delta_p$) | W/kg | 0.94e3 | 1.26e3 | 1.6e3 |
| Electric motor power density ($\delta_{em}$) | W/kg | 2.85e3 | 3.8e3 | 4.75e3 |
| Battery power density ($\delta_b$) | W/kg | 2.25e3 | 3e3 | 3.75e3 |
| Battery energy density ($\delta_e$) | Wh/kg | 135 | 180 | 225 |

**Table 13** OFAT sensitivity analysis dry mass computation

| | Electric pump-fed system dry mas computation | |
|---|---|---|
| | − 25% (kg) | +25% (kg) |
| Pump efficiency ($\eta_p$) | 18.9 | 16.6 |
| Electric motor efficiency ($\eta_{em}$) | 17.8 | 17.2 |
| Pump power density ($\delta_p$) | 18.4 | 16.8 |
| Electric motor power density ($\delta_{em}$) | 17.6 | 17.4 |
| Battery energy density ($\delta_e$) | 18.4 | 16.8 |

**Table 14** Propellant and pressurant gas volumes

| | Kick stage configuration | |
|---|---|---|
| | Proposed system | Legacy system |
| Pressurant gas volume | 8.8 l | 15.3 l |
| Oxidiser volume | 103.4 l | 104.1 l |
| Fuel volume | 43.4 l | 25.1 l |

### 4.2 Volume Envelope

The difference between toxic and green propellants densities and mixture ratios leads to a difference in tank volumes. Likewise, the difference in tank pressures leads to different pressurant gas mass requirements and, therefore, volumes. These values are independent of the pressurisation method selected, and therefore, they are just included here for the sake of completeness.

Table 14 presents the computed pressurant and propellant volumes for both configurations.

### 4.3 Electric Pump-Fed System Power Budget

The electric power that needs to be provided by the battery pack to actuate the pumps is 1.74 kW.

As mentioned in Sect. 3.2, the defined architecture is not design representative, and therefore, more accurate power budgets will be provided when the additional components for both configurations are defined.

What shall be highlighted at this stage is that, apart from the already calculated power, the power required for valves and the rest of the instrumentation shall be very similar for the pressure and electric fed configuration and hence, not relevant for the comparison purposes that is the main objective of the paper.

## 5 Conclusions and Way Forward

This paper studies the performance of an electric pump-fed kick stage powered by our selected green combination, i.e., 98% hydrogen peroxide and propane, and compares the result with the legacy system performance, i.e., the performance of a kick stage propelled by toxic hydrazine and nitrogen tetroxide.

Regarding the green propellant choice, a trade-off between vapour pressure and specific impulse is performed to support the selection. Different green compounds are considered to eventually select highly concentrated hydrogen peroxide and propane as propellants.

The specific impulse for each system is then calculated based on the hypothesis that an equal total impulse shall be delivered. Results show that our proposed system can provide a 4 s higher specific impulse than the legacy system when operated within the selected parameters.

In addition, a Matlab model is developed to compute the main pressurisation system masses. A mass budget for both systems is estimated and highlights the convenience of the proposed configuration under the investigated parameters. More specifically, a decrease in dry mass is found, which, together with the higher specific impulse, leads to a lower wet mass. This fact would translate into a payload capacity improvement compared to the legacy solution while enjoying the advantages of using green propellants.

Finally, an OFAT sensitivity analysis regarding the electric pump-fed system dry mass has also been presented. The study concluded that the correspondent system dry mass, when varying its figures of merit by ± 25%, was comparatively lower than for its pressure fed counterpart.

A refinement of the analysis, focusing on validating and optimising the current selected operational parameters and preliminary design, will follow this study to fully determine the advantages of combining electric pump feeding and green propellants.

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## Declarations

**Conflict of Interest** On behalf of all authors, the corresponding author states that there is no conflict of interest.

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