CEAS Space Journal
https://doi.org/10.1007/s12567-024-00557-9

ORIGINAL PAPER

# Overview of system study on recovery methods for reusable first stages of future European launchers

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Received: 22 December 2023 / Revised: 7 May 2024 / Accepted: 31 May 2024

## Abstract

The design of a reusable launch vehicle implies the need to provide for a means to safely retrieve the component to be re-used. Following economic considerations, reusable launch vehicle concepts tend to be designed such that large parts, like entire stages, are to be recovered. These are usually significant in size and weight and have acquired a considerable amount of energy during their primary mission. This poses the challenge of how to recover them in a way that makes it available for further re-uses. In the past and present, different methods were and are used. Depending on the selected recovery method, the system design is very different necessitating different technologies and competencies to be acquired for a successful design. Two major classes of recovery methods can be distinguished: those recovery methods ending with a vertical landing of the reusable stage and those ending with a horizontal landing. Both have their own benefits and drawbacks. In 2016, The German Aerospace Centre DLR has initiated a large in-house study with the aim of investigating, in a comparative manner on system level, both classes of recovery methods on a system level for two-stage-to-orbit launch vehicles with a reusable first stage and an expendable upper stage to be operated within a European context. Fuel choice and engine cycle were major design parameters that were considered during the study. The present paper presents the framework of this study describing the adopted study logic, providing an overview of the major findings obtained at the end of the first study phase and gives an outlook to the work of the second study phase. It ends with providing a view of a possible demonstrator and technology roadmap toward the realization of an operational two-stage-to-orbit launch system with a reusable first stage.

**Keywords** ENTRAIN · Horizontal landing · Reusability · RLV · Space transportation · Vertical landing

### Abbreviations

| | |
|---|---|
| 3STO | Three stage to orbit |
| AEDB | Aerodynamic database |
| AKIRA | Ausgewählte Kritische Technologien und Integrierte Systemuntersuchungen für RLV Anwendungen (specific critical technologies and integrated system investigations for RLV applications) |
| BEO | Beyond Earth orbit |
| CALLISTO | Cooperative Action Leading to Launcher Innovation for Stage Toss-back Operations |
| C | Carbon/methane |
| CFRP | Carbon fiber reinforced polymer |
| CFD | Computational Fluid Dynamics |
| CNES | Centre National d'Etudes Spatiales |
| DLR | Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre) |
| DRL | Downrange landing |
| e. g. | *exempli gratia* (for example) |
| ENTRAIN | European Next Reusable Ariane |
| ESA | European Space Agency |
| EU | European Union |
| EVEREST | Evolved European Reusable Space Transportation |
| FALCon | Formation flight for in-Air Launcher 1st stage Capturing Demonstration |
| FB | Fly-back |
| FESTIP | Future European Space Transportation Investigations Programme |
| FLPP | Future Launcher Preparatory Programme |
| GG | Gas generator |
| GLOM | Gross lift-off weight |
| GTO | Geostationary transfer orbit |
| H | Hydrogen |

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| | |
|---|---|
| Hi | High |
| HL | Horizontal landing |
| IAC | In-air capturing |
| Isp | Specific impulse |
| JAXA | Japan Aerospace Exploration Agency |
| K | Kerosene |
| LEO | Low Earth orbit |
| LCH4 | Liquid methane |
| LC3H8 | Liquid propane |
| LH2 | Liquid hydrogen |
| Lo | Low |
| Med | Medium |
| MEO | Medium Earth orbit |
| P | Propane |
| P/L | Payload |
| ReFEx | Reusability Flight Experiment |
| RETALT | Retro Propulsion Assisted Landing Technologies |
| RFA | Rocket Factory Augsburg |
| RLV | Reusable launch vehicle |
| RTLS | Return to launch site |
| SC | Staged combustion |
| SLME | SpaceLiner Main Engine |
| SSO | Sun synchronous orbit |
| SSTO | Single-stage-to-orbit |
| TRANSIENT | Thermalkontrollsystem für wiederverwendbare Träger (thermal control system for reusable launchers) |
| TRL | Technology readiness level |
| TSTO | Two-stage-to-orbit |
| T/W | Thrust-to-weight ratio |
| VL | Vertical landing |
| VTHL | Vertical take-off horizontal landing |
| VTVL | Vertical take-off vertical landing |
| w. r. t. | With respect to |

### Symbols

| | |
|---|---|
| $\Delta V$ | Velocity increment [m/s] |

## 1 Introduction

In the past years, new launch system emerged that allowed reusing major parts, mostly the first stage. This re-introduction of reusability to the space transportation business potentially allows launch cost reductions, thus paving the way to create new markets based on the exploitation of space assets and innovations in space technology [1]. The launch vehicles developed and operated by Space X are the forerunners of this trend, whereas companies continue new developments, sometimes toward a reuse of each element. Further, actors are picking up this trend and develop own systems with the ability to re-fly parts of it.

Parts of the launch system that shall be re-used have to be recovered in a way that minimizes damage to it. This recovery, due to the high energy to be dissipated during recovery, is challenging. Several approaches for this recovery exist, some of them still in concept phase, a few however having been flight-proven.

SpaceX and Blue Origin have chosen the recovery via vertical landing as their baseline approach, a suitable choice considering that both companies plan to send their vehicles to the Moon or Mars where no or very little atmosphere exist which is incompatible with a winged horizontal landing on Moon or Mars surface. Other concepts pursue an approach of horizontal landing using wings for dissipating energy, see Sect. 2 for an overview of some major European studies on reusable launch systems (RLV). Both approaches have their advantages and drawbacks. For instance, where a vertically landing vehicle can do with a comparatively compact landing site, a horizontally landing vehicle needs a runway. In exchange, a horizontally landing vehicle has a higher potential for maneuverability and thus an increased flexibility to manage its flight path than unwinged vertically landing vehicles.

As it is currently unclear what choice would be best suited within a European context and considering this lack of a systematic comparison, DLR initiated in 2016 a system study named “European Next Reusable Ariane” (ENTRAIN) that aims at comparing various return and landing strategies on system level. Its focus is oriented toward two-stage-to-orbit systems (TSTO) with a reusable first stage and an expendable upper stage with vertical lift-off. The decision for or against a specific recovery method is probably one of the most significant development decisions made during the early concept phase of a launcher development program. It will determine the accompanying technology development roadmap and the tests to be performed to which significant financial resources will have to be dedicated. As such, there is a financial interest in consolidating the trust in this decision at an early stage as best as possible as later changes would come at significant costs and planning setbacks [2].

This paper gives an overview of the study approach, the adopted down-selection process and its major findings. It concludes with a brief overview of the DLR vision of a technology and demonstrator roadmap toward a European reusable launch vehicle considering current European technology and demonstrator development initiatives and an outlook on the continuation of the ENTRAIN study. Further papers are dedicated to provide more detail on the system design and specific technical aspects, see [3–6], and [7].

## 2 Related research

Several system studies in Europe for reusable space transportation systems were performed throughout the past decades. This section attempts to provide an overview of these studies without claiming to be exhaustive due to the wealth of studies performed in Europe.

The Future European Space Transportation Investigations Programme (FESTIP) launched by the European Space Agency (ESA) in 1994 compared various fully reusable concepts spanning from those foreseeing all stages being recovered to so-called "semi-reusable" ones for which some stages are not recoverable. The investigated concepts included two-stage-to-orbit (TSTO) concepts and single-stage-to-orbit (SSTO) concepts. All concepts but one belong to the vertical take-off horizontal landing (VTHL) category, the only exception being a vertical take-off vertical landing (VTVL) SSTO vehicle that was later dropped from further considerations due to the challenges imposed by the SSTO configuration. An overview of this study can be consulted in references [8, 9], and [10].

In 2001, the French space agency CNES attributed a contract to European space industry for the Evolved European Reusable Space Transportation (EVEREST) study of a fully reusable space transportation concept, [11, 12]. The first study phase aimed at identifying promising VTHL configurations with a payload capability of 7.5 metric tons into Geostationary transfer orbit (GTO) with staging velocity being one major trade-off parameter. One configuration was then selected and analyzed in-depth during the second phase of the EVEREST study.

In parallel to the EVEREST study, French industry under CNES contract has engaged in the system study of a partially reusable concept with a reusable first stage and an expendable second stage, [13]. This concept baptized "Reusable First Stage" or "RFS" is composed of a winged reusable booster stage and an expendable upper stage designed to lift 7.5 metric tons into GTO. While it was considered that from an economical point of view a fully reusable launch system like those studied in EVEREST was preferable, a mix of reusable and expendable stages appeared more easily accessible, see [13].

Other partially reusable concepts studied in Europe are those that foresaw the replacement of the solid boosters of the Ariane 5 launch system by two liquid "fly-back boosters", like the French–Russian study on the Bargouzin concept, [13], the Russian Baikal concept [14] and the German ASTRA study (see Fig. 1), [15, 16]. Both concept proposals investigated liquid-propelled winged boosters which were to accelerate alongside the expendable central core stage of the Ariane 5 rocket and to return to Kourou after separation by making use of air-breathing propulsion.

**Fig. 1** Artist's view of the ASTRA concept, [16]

Some RFS variants with a reusable first stage and one or more expendable upper stages were investigated as well, the reusable first stage being very similar in geometry to that proposed for the fly-back booster concepts [16].

With the successes of the VTVL approach adopted by SpaceX, several system studies in Europe focused on this recovery method. With its Ariane NEXT concept, [17], CNES proposes a VTVL space transportation system as a successor to Ariane 6 that follows a mixed expendable/reusable exploitation scheme, which is the first stage shall only be recovered in about 50% of the missions with the high-energetic missions such as GTO to be performed without recovery. The investigated concepts were TSTO configurations and configurations with liquid expendable boosters or with liquid recoverable boosters following a common core strategy with boosters and central core stage being, in principal, identical. All stages were to be propelled by liquid methane.

In [18], another building block concept based on the VTVL approach is developed and a critical comparison to a "big-size-fits-all" approach based on the VTHL launch and recovery method is performed. This latter concept, dubbed RLVC4 uses a winged first stage recovered with the in-air-capturing method and is sized big enough to transport large payloads but smaller payloads as well thus offering a wide range of payload transportation services. This is to be accomplished by exchanging the expendable stages adapted to the respective launch needs. Figure 2 presents three launcher architectures for this approach.

The EU-funded project RETALT investigated, among others, a VTVL two-stage-to-orbit concept, that could either perform a return to launch site (RTLS) mission scenario where the reusable first stage performs a boost-back maneuver in order to return to the launch site for a vertical landing or a down range landing (DRL) where it will land on a ship positioned downrange of the launch trajectory, [19, 20].

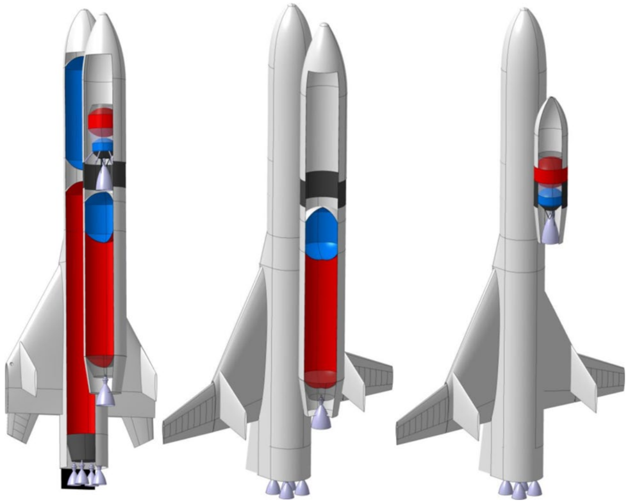


**Fig. 2** Launcher architecture sketches of RLVC4-B configuration as 3STO (left), TSTO (center) and Mini-TSTO (right) [18]

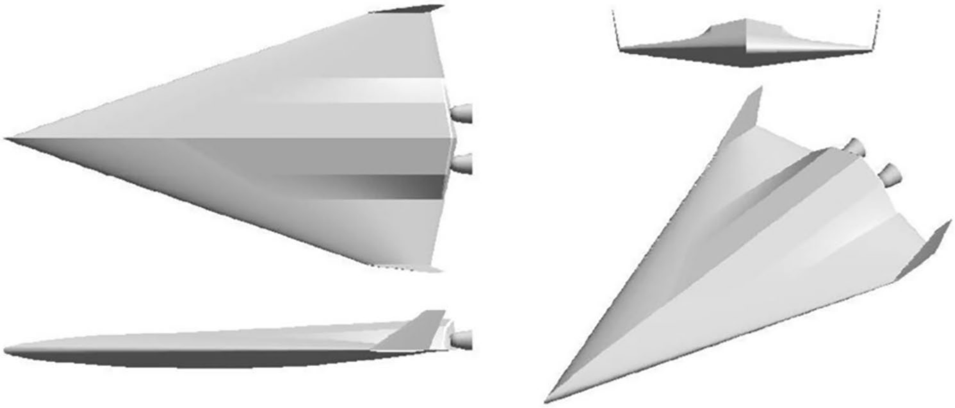
A few studies investigated how various fuel choices impact the design of (partially) reusable launch vehicles. In 2004, results of a comparison between kerosene and methane for the reusable fly-back boosters performed in DLR were published, [21], on the basis of the liquid fly-back booster concept as presented in [15] and [16]. Another study performed in 2020 investigated VTVL TSTO concepts with a reusable first stage and the impact of propellant choice (LOX with LH2, kerosene or liquid methane) on the overall architecture, making use of a multi-disciplinary optimization process and strongly simplified models [22].

The overwhelming majority of these investigations in Europe are based on a pre-selection of the recovery methods pointing to the need of performing a more systematic comparison between those two fundamentally different recovery methods of vertical or horizontal landing. No concept with horizontal take-off was considered as it is the vertical take-off that is already mastered in Europe and likely would preemptively exclude vertical landing as an option for such a vehicle. However, concepts with horizontal take-off and horizontal landing (HTHL) are part of the study portfolio of Europe, with the Sänger Concept of the 80 s (see [23]) and the Aurora concept (see Fig. 3) to name as a current project [24].

Of course, outside of Europe, a considerable amount of research activities on reusable launch vehicles exist, past and present. A good overview extending to non-European research on reusable launch vehicles under consideration of technology aspects is given by [25]. In the United States alone, the range and variety of research activities, past and present, is enormous, ranging from the first concept studies on the Space Shuttle [26] to the X-37 [27] as representative to winged reusable vehicles to the SpaceX Starship [28] as representative for vertically landing reusable vehicles and for a mixed approach in what concerns the orbital stage of the Starship.

The ENTRAIN study initiated in 2016 by DLR aimed at complementing the rich history of system studies in Europe with a systematic comparison of recovery methods for reusable first-stage TSTO concepts while considering the use of different fuel and engine cycles. It was considered essential for a reliable data basis to perform full system loops on a preliminary design level including coupled trajectory optimization for ascent and descent, mass estimation, and calculation for trimmed aerodynamics where necessary. Details of the design process can be found in [3] and [4]. A direct and detailed comparison of the results can be consulted in [6]. Just recently, cost estimations were completed and can be consulted in [7]. The results obtained by the time of the first milestone concluding the first study phase ENTRAIN 1 are presented in a series of papers of which this paper will lay out the framework of this study and a brief summary of the major findings.

**Fig. 3** Preliminary geometry of the Aurora-R2 concept [24]



## 3 Study approach

The primary objective of the study is to systematically investigate, on system level, several recovery strategies for TSTO launch systems with a reusable first stage based on realistic data ensuring a feasible design. The considered recovery strategies can be declined into two categories with respect to their landing approach that is either vertical or horizontal and which has a considerable impact on the stage architecture.

In addition, it aims at providing data that shall help to identify those design choices that could contribute to a promising launch system with a reusable first stage, such as fuel choice and engine cycle. As elaborated below, this led to a considerable number of variants to be investigated. It was therefore decided to adopt a two-stage study approach in order to allow limiting the design effort without loss of quality of the results with respect to the primary objective of the study.

### 3.1 Principal study logic

During the first study phase (ENTRAIN 1), a parametric study was performed that aimed at evaluating the impact of major design drivers on system design and comparing the variants with respect to performance parameters, such as gross lift-off mass (GLOM), dry mass, encountered loads, and impact on launch costs. This way, certain key design choices (fuel combination, engine cycle…) should be evaluated and the most promising ones being identified.

To this end, other design parameters were kept identical irrespective of the considered launcher variant. These design parameters which were kept constant throughout this first study phase are:

- The design mission: GTO with a payload requirement of 7 T plus 500 kg performance margin,
- Vertical take-off from Kourou,
- The basic architecture being fixed to a two-stage-to-orbit (TSTO) concept with a reusable first stage and an expendable upper stage,
- Both stages using the same engine type albeit with a different nozzle to accommodate for the different operative environments (operation in atmosphere or vacuum), and
- No strap-on boosters.

Three different staging points, expressed as effective propulsive $\Delta V$ of the expendable upper stage, were fixed for each investigated variant. Each investigated variant underwent an iterative design process involving mass estimation, aerodynamic data basis generation based on the geometry, engine system definition based on an inhouse engine data basis and coupled trajectory optimization both for ascent till orbit and return leg of the first stage. Ascent and return trajectories were subject to appropriate trajectory constraints such as maximum dynamic pressure or lateral load factor. The variants were iterated until the obtained performance hit the tolerance box of ± 150 kg about the target performance. After the completion of an initial preliminary design phase within this first ENTRAIN study, configurations that showed excessive sizes or did not converge were discarded from further detailing. Further details on the design process can be found in [3] and [4]. Details on the engine data base are provided by [5].

This approach of fixing certain parameters irrespective of the considered concept has a strong risk of not leading to the most optimal design per concept. This could hence conflict with the primary objective of this parametric study, which is to identify the impact of key design parameter on the launch system design and to compare the two recovery strategies under realistic conditions as this is not how a launch system would be optimized in real life for which key design parameters will be adapted to the specific needs of the individual design objective. For instance, fixing the system architecture to TSTO excluding three-stage-to-orbit configurations may penalize some variants more than others but was adopted nonetheless as it is expected to reduce complexity and reduce the relative portion of expendable parts. With this in mind, a second phase of the study, ENTRAIN 2 [29], followed with the purpose to compare an optimally designed VTVL launcher to an optimally designed VTHL launcher. This optimization should be performed within a European context and considering realistic boundaries and a mission scenario with a set of missions accessible to a European launcher.

A selection process was set up at the end of phase 1 in order to limit the number of launch concepts to be optimized while keeping in mind that the two fundamentally different return strategies of vertical and horizontal landing should be compared. This selection process aimed at identifying the most promising set of key design parameters within each of both return strategy categories. The outcome was the definition of a set of key design parameters for one VTVL and one VTHL launch concept to be further investigated in phase 2. Section 3.5 will provide details of the selection process and its results.

### 3.2 Adopted design process

The adopted design process globally follows the NASA launcher vehicle design process as laid out in [30] with some minor adaptations. The achieved design level partially exceeds the state achieved during the Conceptual Design stage and, as such, contains already some relevant elements from the Preliminary Design stage, such as the Preliminary Design Concept and partially Refined Top-Level Requirements [30], and includes a concept design of major hardware subsystems up to the third level of the compartmentalization scheme (e. g. to aeroshell and tankage level) as described in [30].

Involved discipline functions following [30]) were:

- System,
- Trajectory,
- Aerodynamics,
- Control (simplified static trim analysis for VTHL only),
- Structures,
- Thermal, and
- Propulsion.

For details on the technical design process, it is recommended to refer to [3] and [4].

Certain disciplines mentioned by NASA in [30] were not involved in the ENTRAIN-study-design process as such. Since the objective was not to produce an operational launch vehicle, aspects such as manufacturing were not considered. Avionics and materials were not considered beyond mass considerations as well. Finally, while ascent and re-entry trajectories were optimized using algorithm-based optimal control theory, guidance and navigation were not part of the design process neither as perturbations and deviations from the nominal design point were not part of the study.

## 3.3 Investigated take-off mode and recovery strategies

The choice of take-off mode (horizontally or vertically or air-launch) is equally important for the necessary development effort. However, for this study, it was decided to concentrate on the conventional vertical take-off from ground as this approach is well mastered in Europe, and no supplemental technology development effort is required besides the strict minimum to ensure recovery for the purpose of reusing the first stage. The designated launch site selected for this study is Kourou being the Europe's primary Spaceport.

As elaborated in the introduction, the return strategy and landing mode, alongside the take-off mode, is likely among the design choices with the largest impact on the development effort as ground and flight demonstration effort and specific technology development depends on this choice, whereas for a horizontally landing (or take-off), for instance, wings are needed that allow the vehicle to be safely operated throughout a wide range of Mach numbers, a vertically landing stage requires a highly reactive throttle capability for its rocket engines, among others. While both recovery approaches are mastered (by SpaceX and Blue Origin) or have been mastered in the past (as for the Space Shuttle), the associated technologies and the capabilities have to be acquired or further developed in Europe. This reasoning led the study team to place the focus on the return strategies and landing mode. Four different return strategies, sorted by their landing mode (horizontally or vertically), have been investigated as described below:

### 3.3.1 Vertical landing

- Return to launch site (RTLS), see Fig. 4 left side: This return strategy is identical to that used by Falcon 9 on low-performance missions and for the boosters of Falcon Heavy. After separation of the upper stage, the reusable stage performs a rotation maneuver and then fires its engines in order to reverse the flight direction thus reducing the distance to the launch site. After this boost-back maneuver, the stage is again rotated in order to orient the

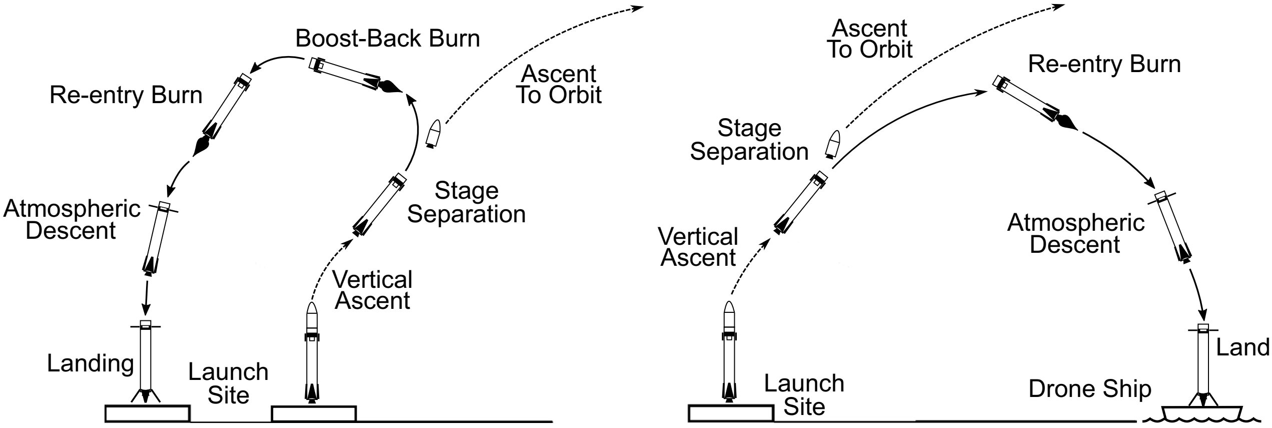


**Fig. 4** Return strategies for VTVL: Return to launch site (left) and downrange landing (right)

stage that its engines point in-flight direction. Another engine boost phase may be programmed to decelerate the stage for load reduction. Above the landing platform, legs are extended and the stage is further decelerated by the landing boost until touchdown. At this point and anticipating study results, it shall be mentioned that RTLS investigation was discontinued as its performance was disappointing within the frame of the study constraint that limited the mission to the high-energy GTO mission and to a TSTO configuration. This result does not disqualify this specific recovery method for other launch scenarios or other architectural choices such as three stage to orbit.

- Downrange landing (DRL), see Fig. 4 right side: After separation, the lower stage is rotated before firing its engines in order to decelerate the stage to minimize reentry loads. Unlike RTLS, the flight direction is not reversed and the stage will land vertically on a platform placed downrange at a suitable position. In most cases, this platform is located on sea such as the drone ship used by SpaceX.

### 3.3.2 Horizontal landing

- Fly-back (FB), see Fig. 5 left side: After separation of the upper stage, the reusable stage will continue its flight downrange until the dynamic pressure is sufficient again to use the lift force generated by wings to point the flight direction to the landing site not far from the launch site. At a suitable point (subsonic), air-breathing engines are ignited in order to cover the remaining distance that separates the vehicle from its landing site.
- In-air capturing (IAC), see Fig. 5 right side: The initial phase of this return strategy is identical to that of a fly-back strategy. However, instead of using jet engines, a towing plane will capture the stage with an appropriate device and tow it back to the landing site where the vehicle will be detached and automatically land on a runway. This strategy allows circumventing the need to install heavy jet engines and does not require additional fuel hence the potential interest of this approach. It shall be noted that the process of in-air capturing method has not been simulated within this study as little repercussions on the performance are expected. However, significant progress has been achieved recently by extensive simulations and lab-scale experiments in the European Commission-funded project FALCon with major results summarized in [31].

It shall be noted that other recovery methods were not considered for this study. Particularly, return methods that combine a boosted phase and a gliding phase such as the “dead leaf” concept were omitted as they showed to be less-performing than the fly-back option, see [32]. However, from a cost point of view, such return methods might still prove competitive as they simplify the recovered stage with respect to the winged concepts presented here.

## 3.4 Additional key design parameters

During the first study phase, further design choices were investigated which also have a considerable impact on technology development effort and on the system design:

- Fuel combinations: liquid hydrogen, liquid methane, and kerosene, all in combination to liquid oxygen, were considered. The impact of sub-cooling and the use of propane as fuel have been examined as well.
- Engine cycle: both gas generator cycles and staged combustion cycles were investigated as engine cycles.

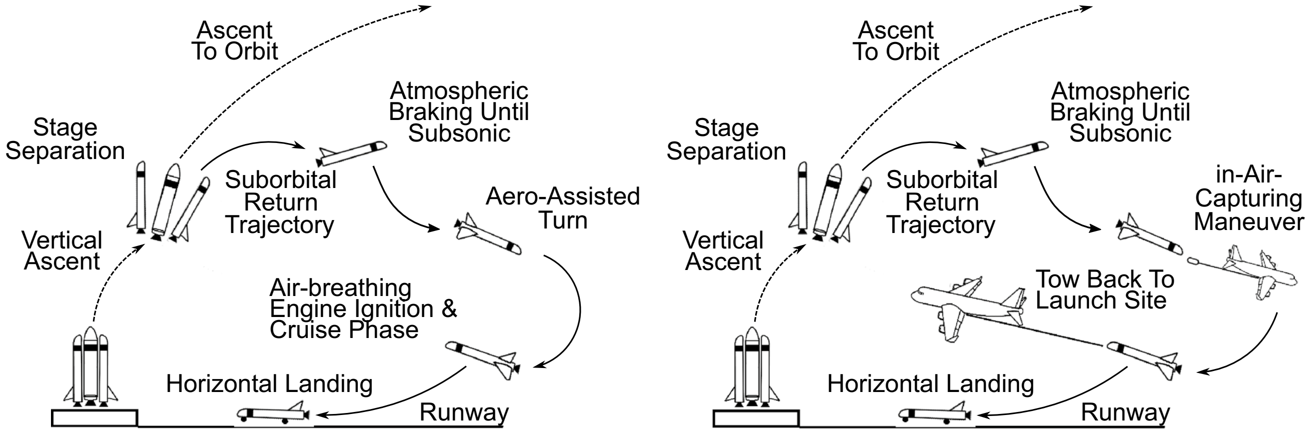


**Fig. 5** Return strategies for VTHL: Fly-back (left) and in-air capturing (right)

In ENTRAIN 1, return strategies, fuel combinations, and engine cycle are the ingredients which make up the definition of a variant that is subjected to a preliminary design process aiming at sizing the launch system in such a way that it meets the mission requirements (minimum performance for a set of missions) and is compatible to applicable constraints such as maximum lateral or axial load factors or maximum dynamic pressures. These three key design parameters alone lead to 24 possible variants disregarding any sub-variants with sub-cooled propellant or more exotic fuels (propane) to be investigated.

Table 1 summarizes the design matrix, whereas Table 2 provides an overview of all investigated variants in the shape of a matrix. The design process was not performed for every variant however due to time constraints as long as the investigated variants allowed a deduction of the benefits or drawbacks on system level of the related design parameter.

For each variant, up to three staging points were used as design parameter. This parameter is expressed as propulsive ΔV of the upper stage, a higher ΔV equating to a bigger upper stage. This parameter is relevant as not only does the staging determine the overall launcher size as there exists a staging that allows maximizing the payload or alternatively minimizing the take-off weight for a given mission requirement, but it also has an impact on the economic balance of a launcher with a reusable first stage. The additional cost benefits expected for a reusable launcher are strongly linked to the cost savings due to reusing a part of the launch system. It can be expected that the cost savings are larger if the re-used part represents a bigger part of the system. A small upper stage will require a larger first stage in order to compensate for the reduced ΔV of the upper stage hence a larger portion of the launcher is re-used in this case. However, at the same time, a larger first stage and a smaller upper stage increase the energy state of the first stage after separation from the second stage. This not only induces more effort to limit the reentry loads but may for some return strategies also lead to larger distances to the landing site. Both effects impact the launcher design and to some extent the maintenance and refurbishment effort for the reusable stage. In Table 1, the upper stage ΔV is depicted while the classification is with respect to the Mach number of the first stage separation. A launcher with a designation of Hi for "high" has a separation of the first stage at a Mach number between 10 and 12 while a Lo for "low" classified launcher separates its first stage at a Mach between 6 and 7.5.

**Table 1** Design Matrix of ENTRAIN study with nomenclature abbreviations

| Design Parameter | Description | Nomenclature |
|---|---|---|
| Return Method | VTVL Downrange Landing | VL DRL |
| | VTVL Return-to-Launch-Site | VL RTLS |
| | VTHL In-Air-Capturing | HL IAC |
| | VTHL Fly-Back | HL FB |
| Propellant | LOx-LH2 | H |
| | LOx-LCH4 | C |
| | LOx-LC3H8 | LC3H8 |
| | LOx-RP-1 | RP-1 |
| | Hybrid | Hybrid |
| Engine Cycles | Staged Combustion | SC |
| | Gas Generator | GG |
| Upper Stage Δv (First stage separation Mach) | 6.6 km/s (Mach 10–12) | Hi |
| | 7.0 km/s (Mach 8.5–9.5) | Med |
| | 7.6 km/s (Mach 6.0–7.5) | Lo |

## 3.5 Selection process

As indicated earlier, the number of variants investigated in the first study phase ENTRAIN 1 was quite large limiting the study approach to that of a parametric study with a limited detail level. A down-selection to two competing concepts was set up in order to increase the study detail level and allow an optimization process closer to operative mission requirements. To this end, a suitable selection process had to be established.

As a first step, appropriate selection criteria had to be identified. Out of 18 potential selection criteria candidates, seven were selected in a common team effort in order to smooth out any bias as much as possible. No threshold criteria were identified as all variants that did not meet the performance requirement of ENTRAIN 1 or which proved to be technically infeasible (e.g., unmanageably excessive loads) were dropped prior to be subjected to the selection process. The used selection criteria alongside indicative evaluation guidelines are presented by Table 3.

**Table 2** Investigated variants

| | | **LOX/LH2** | | **LOX/LCH4** | | **LOX/RP1** | | **LOX/LC3H8** | |
|---|---|---|---|---|---|---|---|---|---|
| **Return Strategy** | | **GG** | **SC** | **GG** | **SC** | **GG** | **SC** | **GG** | **SC** |
| **VL** | **RTLS** | ● | ● | ● | ● | ● | ● | - | - |
| | **DRL** | ● | ● | ● | ● | ● | - | ● | - |
| **HL** | **FB** | ● | ● | ● | ● | ● | ● | - | - |
| | **IAC** | ● | ● | ● | ● | ● | ● | ● | - |

**Table 3** Selection criteria and evaluation guidelines

| Criteria | Evaluation guideline |
|---|---|
| Launch Costs | *Positive*: Lower expected costs: low dry mass, less expected maintenance (e. g. due to low TPS mass, few engines, less expected integration effort, high number of reuses)<br>*Negative*: Higher expected costs: high dry mass, higher expected maintenance (e. g. due to high TPS mass, many engines, higher expected integration effort, low number of reuses) |
| Development Costs | *Positive*: Technologies predominantly high TRL, existing experience in Europe, low dry mass, relatively simple design, low number of testing required<br>*Negative*: Technologies predominantly low TRL, lacking experience in Europe, high dry mass, relatively complex design, high number of testing required |
| Development Risk | *Positive*: Existing experience in Europe, proven techno (i.e., existing examples of use around the world), little in-flight testing required, simple switch to back-up solution w/o or little re-design, low operational or layout complexity; possibility for step-wise transition to concept<br>*Negative*: lacking experience in Europe, unproven techno (i.e., no existing examples of usage around the world), intensive in-flight testing required, difficult switch to back-up solution w/ considerable re-design, high operational or layout complexity; disruptive transition to concept necessary |
| Growth/Shrink potential | *Positive*: High scalability of layout with comparatively simple re-design<br>*Negative*: Low scalability of layout requiring large re-design |
| Mission flexibility | *Positive*: Limited impact on loads and structural layout; simple integration of additional performance-enhancers (e.g. boosters)/high potential for modularity; sufficient performance in other orbits<br>*Negative*: Strong impact on loads and structural layout; difficult integration of additional performance-enhancers (e.g. boosters)/low potential for modularity; insufficient performance in other orbits |
| Reliability | *Positive*: Low complexity of concepts, ops & mission, large number of proven technologies, low number of moving parts<br>*Negative*: high complexity of concepts, ops & mission, large number of little proven technologies, large number of moving parts |
| Environment | *Positive*: Environmentally friendly (production of hardware & fuel, exhaust gas, end-of-life disposal…)<br>*Negative*: Not environmentally friendly (production of hardware & fuel, exhaust gas, end-of-life disposal…) |

Special care had to be taken considering that this down-selection was to be performed at a very early stage when data and results are still subject to considerable uncertainties and the study approach was that of a parametric study during ENTRAIN 1. It should be avoided that principally promising concepts or key design parameters are prematurely discarded because another one was numerically slightly better but with a difference probably still within the error bar. With this in mind, it was decided to evaluate each variant qualitatively only by comparing pairs of variants considering their performance with respect to each selection criteria. This evaluation was performed as a team effort as well, again with the aim to smooth out possible biases of individual members of the evaluation team. Comparing each candidate pair-wise led to a ranking of the candidates with respect to the criteria under consideration. Finally, per criteria, the best and worst performing variants were identified with all other variants being classified as neutral. In the case of two candidates being evaluated as being very similar to each other during the pair-wise evaluation, they were considered to perform identically well with respect to the criteria under consideration.

Ideally, the resulting table performance vs criteria should show an accumulation of positive evaluation for one variant with further neutral and little or no negative evaluations. Both VTVL and VTHL variants were evaluated separately yielding two tables. The results of the selection process are presented in 4.2.

Apart from the evaluation of the development costs for the engine, criteria were applied to the entire launch vehicle. For certain cases, this might lead to a better evaluation of the vehicle despite the engine cycle of that specific variant performing worse with respect to that criteria.

Since no work was performed on ground infrastructure or ground operations, these aspects could not be part of the evaluation at this stage. As such, the evaluation result is limited to the performance of the vehicle alone with respect to the selection criteria.

## 4 Results overview

In this section, we will present major findings of the first study phase ENTRAIN 1 including the results of the selection process prior to the beginning of the ENTRAIN 2 study phase. This will be complemented by a discussion of the major conclusions drawn from these results.

During this study phase, a total number of 19 configuration, disregarding any abandoned concepts such as RTLS, were investigated. For each concept, several design loops including coupled optimization and simulation of ascent of the launcher to orbit and re-entry of the first stage, aerodynamic performance calculation, and mass estimations were run until a consistent design respecting the requirements was obtained. This meant that on average, a minimum of ten design loops were performed per concept with some concepts requiring significantly more iteration loops before reaching convergence. Details on the design loops can be consulted in [3] and [4].

These concepts could resort on an extensive propulsion database encompassing 36 engines for which performance and design parameters were calculated, see [5]. This database included:

- 19 gas generator cycle engines, and
- 17 staged combustion cycle engines.

Within these engines, four propellant combinations and seven nozzle expansion variations were considered and a total of ten thrust chamber geometries were defined. With a few exceptions, these cycles were analyzed with two independent cycle analysis tools in order to consolidate performance data.

### 4.1 Results of ENTRAIN phase 1

Several characteristic features of the investigated variants were identified as a relevant means of comparison (see [6]). Among these features, the Gross Lift-off Mass (GLOM) is a comparatively good indicator of the size of the launch configuration within a propellant type class. In between different propellant type classes, a comparison is more difficult due to different densities and mixture ratios since fuel mass has a different impact on launch costs and is a consumable, whereas hardware, at least that of the first stage, is to be re-used.

Irrespective of this, a comparison over a variety of propellant type allows drawing a conclusion about the required take-off thrust and hence about the number, size and performance requirements for the propulsion system of the first stage. A higher number of engines increase the complexity and the cost of a system. As such, a system with lower thrust requirement is preferable when all others parameters were identical.

At this point, it shall be noted that all VTVL RTLS variants were discarded from further considerations at an early stage of the study as they led to excessively large launch systems due to the choice of GTO as reference mission. The high energy requirements of this mission led to increased fuel quantities required to perform the boost-back maneuver despite the fact that the trajectory optimization process used aimed at finding a suitable compromise between ascent and descent for this particular return method in order to maximize the performance. This left the downrange landing (DRL) as the preferred recovery method for the GTO mission and for all VTVL variants. RTLS was considered again in the second phase of this study ENTRAIN 2 as a potential recovery method for less energetic missions.

Figures 6 and 7 summarize selected mass characteristics of the investigated variants. For quick referencing, following nomenclature is adopted for variant identification. A variant is designated by its recovery attitude (VL: vertical landing, HL: horizontal landing) followed by precisely following the recovery method (DRL: downrange landing, RTLS: return to launch site, FB: fly-back, IAC: in-air capturing). The

**Fig. 6** Groff lift-off masses (without payload mass) of investigated variants

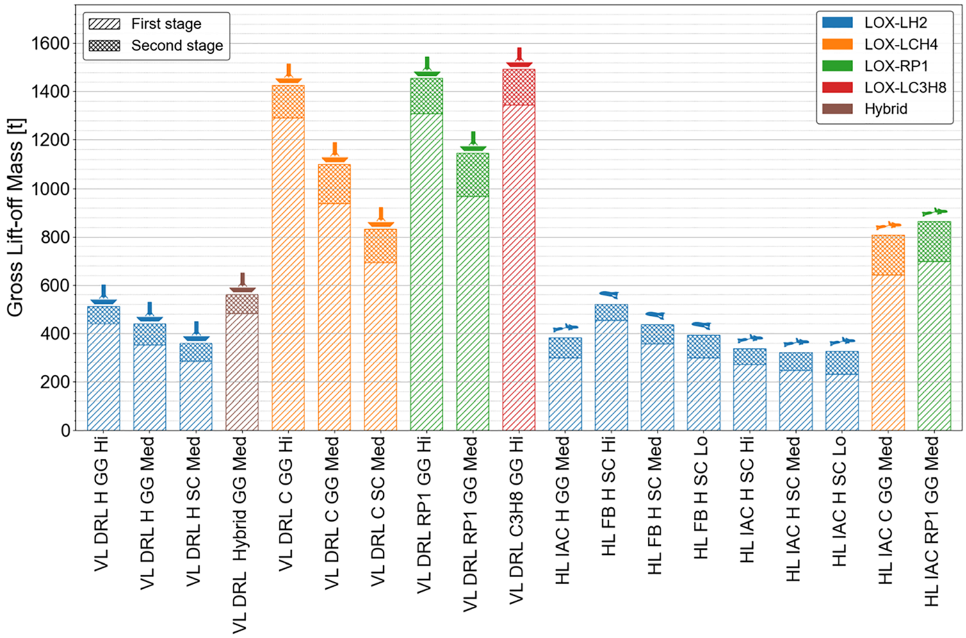
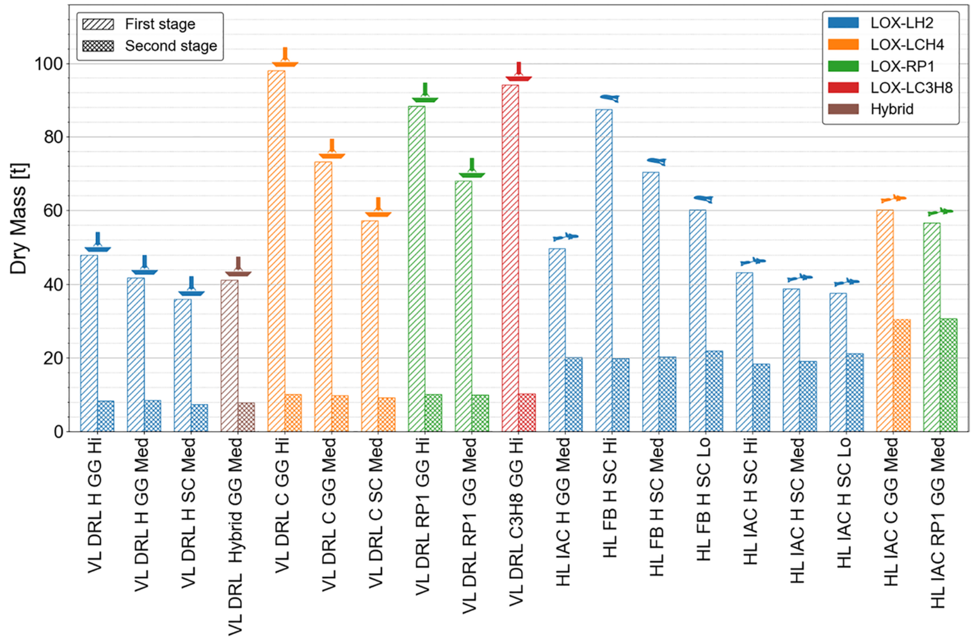


**Fig. 7** Dry masses of investigated variants



ensuing section describes the two stages by designating with the first letter the used fuel type (H: hydrogen, C: methane, P: propane, K: kerosene) in the first stage followed by the loaded propellant in metric tons. An identical logic applies to the second stage. Finally, the used engine cycle (GG: gas generator, SC: staged combustion) and the ΔV-class (see Table 1) of the upper stage are given.

Figure 6 shows the GLOM minus the payload mass allowing distinguishing the first stage and second stage contribution. As can be seen, the values for the total GLOM of hydrocarbon-fueled launchers exceed by far those relying on hydrogen fuel. A factor of two exists between a hydrogen-driven VTHL with an in-air capturing recovery strategy and a methane-driven one. This factor increases when comparing hydrogen VTVL to methane VTVL launch systems. This is due to the fact that hydrocarbon-based propulsion systems generate significantly lower specific impulses than hydrogen-based ones. This fact has multi-fold consequences on the design of a TSTO launch system with a reusable first stage:

- The lower specific impulse leads to increased fuel mass required to deliver the necessary ΔV. This will lead to larger and heavier stages, including a heavier upper stage compared to a hydrogen-fueled upper stage delivering the same ΔV.
- A heavier upper stage will result in reduced accelerations to be compensated by adding further fuel to the first stage. Consequently, the first stage has to increase in size and mass.
- Launch systems relying on recovery strategies that make use of the primary fuel will also suffer performance penalties when using hydrocarbon fuel instead of hydrogen. This is particularly true for all VTVL concepts since a significant ΔV requirement for deceleration and landing boost has to be accounted for. This penalty is further aggravated by the fact that this fuel mass has to be accelerated during ascent thus further decreasing accelerations delivered by the first stage.

Figure 7 presents the obtained dry masses of both stages for each investigated variant. These figures are of interest as the production costs are to some extent related to this figure. When considering launch costs, it is also interesting to distinguish between production costs and fuel costs as the value of a kilogram hardware can be expected to be noticeably different from the value of a kilogram fuel. Furthermore, the treatment of hardware and fuel for launch cost evaluation has to be different for reusable launch systems, the hardware being purchased only once or for a limited number, whereas fuel has to be produced for each flight.

Comparing the VTVL DRL, all-hydrogen variant with a medium-sized upper stage (MED) with its equivalent using methane for the first stage and hydrogen for the upper stage indicates the impact that the switch from using hydrogen in the first stage to a hydrocarbon fuel has. The upper stage being in size and mass very close to each other as they deliver the same Δv and use the same fuel the difference in dry mass on the first stage is only related to the increase in fuel mass necessary to compensate for the lower specific impulse of methane. This underlines the negative effects hydrocarbon has on the performance of launchers.

It shall be emphasized that the limitation to a TSTO configuration has of course an impact on the mass budgets.

Specifically, for GTO missions, a three-stage configuration or a two-stage configuration with side boosters may be beneficial in terms of launcher size and mass. A switch to a different staging may prove specifically beneficial for the hydrocarbon variants performance-wise. This however was beyond the study scope. In [18], a family of launchers approach that includes TSTO and three stage to orbit (3STO) is discussed.

The same tendencies as for the GLOM can be observed for the dry mass of the first stage although to a lesser extent. Indeed, the more favorable structural index for the hydrocarbon-fueled variants alleviates to some extent the penalizing impact of the specific impulse—albeit not sufficiently to compensate it. The hydrogen-fueled variants continue to perform significantly better.

Whereas all-hydrogen variants maintain the edge in terms of performance, hydrocarbon has some interest particularly for a reusable first stage. The chances are good that when using hydrocarbon fuel no particular tank insulation is needed unlike for hydrogen. Ground handling and storage is also simplified; however, this benefit is mitigated to some extent when using a mixed fuel approach with hydrocarbon in the lower and hydrogen in the upper stage. Using two different fuel types for the first and upper stage also imposes the development of two separate engines and two separate production lines and increases launch installation and preparation complexity against which the performance benefit with respect to an all-hydrocarbon vehicle has to be traded.

Yet, an all-hydrogen launcher both has the better performance and avoids the need to handle two types of fuel but being a cryogenic liquid requires additional care.

Figure 8 provides an overview of selected VTVL and VTHL variants resulting from the system loop. For size comparison, Ariane 5 and the Falcon 9 launcher are represented as well.

**Table 4** Evaluation of VTVL variants

| | Recovery method | DRL | | | | | |
|---|---|---|---|---|---|---|---|
| | Fuel combination | C | | H | | RP1 | |
| | Engine cycle | GG | SC | GG | SC | GG | SC |
| **Launch costs** | | ☹ | ○ | ○ | ☺ | ☹ | ○ |
| **Development costs** | **System** | ☹ | ○ | ○ | ☺ | ☹ | ○ |
| | **Engine** | ○ | ☹ | ☺ | ○ | ○ | ○ |
| **Development risk** | | ○ | ○ | ☺ | ○ | ○ | ○ |
| **Growth/shrink potential** | | ○ | ○ | ☺ | ☺ | ☹ | ☹ |
| **Mission flexibility** | | ○ | ○ | ☹ | ☹ | ☺ | ☺ |
| **Reliability** | | ☺ | ○ | ○ | ☹ | ☺ | ○ |
| **Environment** | | ☹ | ○ | ○ | ☺ | ☹ | ○ |

☹ negative ☺ positive ○ neutral

## 4.2 Results of the selection process

The result of the evaluation process for the selection process as described in 3.5 is shown for the VTVL versions in Table 4, whereas those for the VTHL is presented by Table 5. It shall be reminded that not every variant was investigated to full detail and some were abandoned. However, the vast database available during this evaluation process allows transposing tendencies observed for fully investigated candidates to others. For instance, it can be expected with good confidence that hydrocarbon-fueled variants will always lead to higher gross lift-off masses than hydrogen-fueled ones, irrespective of recovery method.

It is emphasized that the evaluation was performed within each overall recovery category, which is within VTVL and within VTHL separately. This does not allow comparing the evaluations of a VTVL variant to a VTHL variant. For instance, it is expected that test effort for a VTVL engine will be significantly higher than for a VTHL engine since the former has to offer deep throttling capabilities representing considerable design challenges and which will have to be validated by additional test runs not necessary for engines with only limited throttling requirements.

Overall, the hydrogen-fueled variants received the best evaluation. It shall be noted that since all RTLS variants have been discarded from further considerations due to their

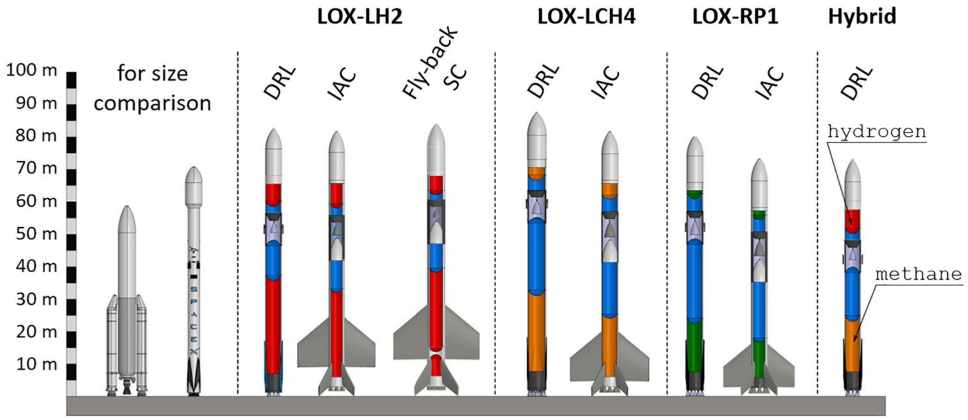


**Fig. 8** Geometry and layout of selected RLV of the ENTRAIN study compared to Falcon 9 and Ariane 5

**Table 5** Evaluation of VTHL variants

| Recovery method | | FB | | | | | | IAC | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel combination | | C | | H | | RP1 | | C | | H | | RP1 | |
| Engine cycle | | GG | SC | GG | SC | GG | SC | GG | SC | GG | SC | GG | SC |
| **Launch costs** | | ☹ | ○ | ○ | ○ | ☹ | ○ | ○ | ○ | ○ | ☺ | ○ | ○ |
| **Development costs** | **System** | ☹ | ○ | ○ | ○ | ☹ | ○ | ○ | ○ | ○ | ☺ | ○ | ○ |
| | **Engine** | ○ | ☹ | ☺ | ○ | ○ | ○ | ○ | ☹ | ☺ | ○ | ○ | ○ |
| **Development risk** | | ○ | ○ | ☺ | ○ | ○ | ○ | ○ | ○ | ☺ | ○ | ○ | ○ |
| **Growth/shrink potential** | | ○ | ○ | ○ | ○ | ☹ | ☹ | ○ | ○ | ☺ | ☺ | ○ | ○ |
| **Mission flexibility** | | ○ | ○ | ☹ | ☹ | ○ | ○ | ○ | ○ | ○ | ○ | ☺ | ☺ |
| **Reliability** | | ☺ | ○ | ○ | ○ | ☺ | ○ | ○ | ○ | ○ | ☹ | ○ | ○ |
| **Environment** | | ☹ | ○ | ○ | ☺ | ☹ | ○ | ☹ | ○ | ○ | ☺ | ☹ | ○ |

☹ negative ☺ positive ○ neutral

excessive lift-off mass, they were not subjected to the evaluation. Since no development program for propane as a rocket fuel for the relevant thrust class existed in Europe, these variants were also not considered for further investigation.

The following section establishes the reasoning behind the evaluation result. It shall be highlighted that this reasoning is based on engineering judgement on a preliminary basis and against the backdrop of a limited data base available for each variant.

#### 4.2.1 Recovery by vertical landing (VTVL)

For this landing strategy, the hydrogen variant sporting gas generator engine cycle came out winner of the selection process closely followed by the hydrogen variant with staged combustion engines. While the staged combustion engine variants received a favorable evaluation with respect to launch and system development costs compared to the gas generator cycle variant due to its smaller size, it generates additional challenges with respect to reliability due to the particular nature of the closed cycle engine that is difficult to master.

It shall be noted that RTLS was no longer considered during this evaluation process since the obtained performance was very disappointing leading to excessively large launch vehicles and to the conclusion that this recovery method was impracticable for GTO missions.

**4.2.1.1 Launch, development costs and development risk** Concerning launch and system development cost, those VTVL concepts with the lowest gross lift-off mass can be expected to have a certain advantage over other concepts. In ENTRAIN 1, no cost estimation was performed for each variant using the gross lift-off mass as a surrogate instead for the launch costs and the dry mass for the development cost. Most cost estimation tools used in preliminary design stages, like TRANSCOST [33] parametrize the development and launch costs based on a mass breakdown of the object in question. While development costs resulting from such a model are more linked to the dry mass, the gross lift-off weight of the system, albeit together with the dry mass, has a stronger impact on the launch costs.

This approach favors the better performing variants such as the hydrogen-fueled concept with staged combustion engine since these launchers tend to be smaller both in gross lift-off weight and dry mass compared to the hydrocarbon launchers as can be seen in Figs. 6 and 7.

Europe has extensive experience with hydrogen gas generator cycle engines placing this type of engine on the top of the ranking list with respect to the engine development costs and the development risks. Until recently, the staged combustion cycles using any of the two considered hydrocarbon fuels would have been ranked at the bottom for both the engine development costs as Europe lacked any significant experience for either staged combustion engine or the use of hydrocarbon fuel. While the Prometheus X engine, a methane-driven staged combustion engine, is still in its concept phase, [34], not enough to lift it up from the bottom of the ranking, this picture has changed with the successful test runs of the kerosene-driven staged combustion Helix engine of the private European company Rocket Factory Augsburg (RFA). This is the reason why kerosene staged combustion cycle was better evaluated with respect to its methane counterpart placing it in the neutral range.

As for the development risk, this has two-fold aspects. The first aspect is related to the technology readiness level (TRL) in Europe, partially covered already by the engine development cost criteria, and a global TRL. A low global TRL would imply that developers would have to tread unknown territory on many points with a high risk of discovering showstoppers. The mere existence of a foreign working engine can be considered as a proof of concept justifying a favorable evaluation with respect to development risk. Since recent developments (Raptor engine, Prometheus engine, and the Helix engine) showed that all considered propellant-engine cycle combinations are feasible. None was considered negatively leaving the hydrogen gas generator cycle on the top of the ranking due to thorough European expertise and all others neutral.

**4.2.1.2 Growth and shrink potential** The evaluation of the variants was principally based only on the sub-cooling capability of the propellants allowing storing more propellant quantity in the tanks with some impact on the structural design and flight control not assessed at this stage of the study. It was considered that other distinctive characteristics of the investigated variants did not allow discerning them with respect to better or worse growth and shrink potential at this stage of study.

Compared to hydrocarbon variants, the LOX/LH2 fueled variants offer the best growth and shrink potential due to its higher sub-cooling capability. With sub-cooling propellant, more of it can be stored inside the same volume. The density of hydrogen being particularly sensitive to temperature offers an enhanced potential for increasing fuel mass without the need to modify the tank volume. It is obvious that this benefit has to be traded against any additional effort to maintain lower temperatures. This kind of analysis however was beyond the scope of the ENTRAIN 1 study.

For this criterion, the kerosene variants received the worst evaluation as, albeit also benefitting from sub-cooling, does so at a more restricted level than methane. Coupled to the fact that due to the lower mixture ratio of kerosene variants that for methane variants, these candidates even benefit less from a potential sub-cooling of oxygen.

**4.2.1.3 Mission flexibility** Concerning mission flexibility, the evaluation tendency is reversed with the kerosene variants being evaluated as the best performing one and the hydrogen variants receiving the worst evaluation. This evaluation is based on the judgment that concerning in-orbit waiting times for multi-boost missions, non-cooled fuels show superior handling qualities.

**4.2.1.4 Reliability** Concerning reliability, hydrocarbon-fueled variants were deemed to fare better than hydrogen-fueled ones since they require less effort in maintaining the fuel at extremely low temperatures, hence limiting the need for sophisticated insulation concepts that might fail. Additionally, gas generator engines are considered to be more reliable than closed cycle engines as they can run at lower combustion chamber pressure and Europe has decades of experience in operating these engines. This makes the hydrocarbon gas generator variants to be evaluated as more reliable than all other considered variants from a European perspective.

**4.2.1.5 Environmental impact** No specific analysis of the environmental impact nor a life cycle analysis of the launch vehicles from the time of production until its decommissioning could be performed within this parametric study. As a very simplified surrogate approach, smaller launchers are assumed to have advantages as far as the non-propellant parts are concerned as it was considered that the smaller the launcher the less material and less energy is needed for production and less material may prove unrecyclable requiring special treatment.

Additionally, hydrogen combustion does not produce $CO_2$ and is as such more ecologically friendly than any hydrocarbon fuel as long as it is assumed that propellant production itself is ecologically friendly enough. This for instance would require that hydrogen production uses predominantly energy drafted from renewable sources. It was assumed that due to the increase of the share of renewable energies and the drive of the European Union to become $CO_2$-neutral by 2050 and by 2030 having reduced its $CO_2$ production to at least 55% with respect to the state at 1990, this would be the case by the time a European reusable launch system became operational. Additionally, the less fuel quantity needs to be produced, the less energy is consumed. This helps in reducing energy consumption and potential $CO_2$ production. Finally, propellant that can be produced on-site or near its place of consumption allows limiting transport costs and any ecological impact. These considerations led to the hydrogen staged combustion candidates being considered to be environmentally most friendly.

### 4.2.2 Recovery by horizontal landing (VTHL)

Similar reasoning applies to the VTHL variants when comparing cycles and fuel types. Additionally, two recovery methods were part of the evaluation. As the in-air capturing methods (IAC) lead to smaller launchers and offer higher flexibility and growth/shrink potential as, at least within some limits, the towing air plane can be deployed in a flexible way recovering the stage from various points irrespective of inclination and, to some extent, irrespective of distance to the landing spot. It was considered that fly-back variants offer a somewhat lesser flexibility as they rely on high-performance, but relatively low fuel-efficient adapted fighter engines compared to the highly efficient civil turbojet engines of the towing aircraft, and that due to the fixed design, the limits to the range that can be covered with the onboard fuel are more limited. However, the development risk for the in-air capturing is estimated to be noticeably higher as this technology has yet to be developed and demonstrated for this kind of application.

For this category of landing method again, the hydrogen-fueled variants were evaluated more favorably than their hydrocarbon-fueled counterparts. While for the fly-back recovery strategy, this difference is small. It becomes more pronounced for the variants relying on the in-air capturing method. Here, the differences in evaluation between staged combustion and gas generator are less obvious compared to the evaluation of the VTVL configurations.

## 5 Demonstrator roadmap

As highlighted in the introduction, the decision on the recovery mode is of strategic importance when developing a reusable launch system. This development has to be accompanied by developing demonstrators that support knowledge and competence acquisition as a means for development risk mitigation. Ideally, a demonstrator program is set up in parallel to the development program for the operational system while enabling mutual interactions of both programs. This demonstrator program has to be embedded in a technology development program that is dedicated to the acquisition of necessary or desired technologies.

At this stage, no firm commitment for a development of a reusable launch system, let alone a final decision on the preferred recovery mode has been taken in Europe. DLR is developing the Reusable Flight Experiment ReFEx, [35], a winged demonstrator with an emphasis on system design of a maneuverable winged re-entry vehicle mastering the transition from hypersonic to subsonic flight while retaining full controllability.

In addition to ReFEx, DLR is developing, in cooperation with CNES and JAXA, a demonstrator mirroring principal flight phases of a vertical take-off vertical landing reusable first stage, [36].

Both demonstrators are each dedicated to addressing technically challenging aspects specific to VTHL and VTVL reusable first stages. This approach of developing and flying these two demonstrators will contribute to consolidating the knowledge of the challenges and attires of both recovery modes by hands-on experience complemented by further flight demonstration such as FALCon [31]. As these flight demonstrations are comparatively small and only partially covering a life cycle of an operational system, further and larger demonstrators have to follow.

Parallel to this demonstrator activity, a variety of technology development projects are set up in DLR, either fully domestic funded or EU and ESA-funded ones. Such technology DLR projects are AKIRA, [37, 38], focusing on efficient stage return, reusable cryogenic tank insulation, and structural technologies for RLV stages and TRANSIENT, [38], a follow-up project to AKIRA focusing on cryogenic insulation technologies for RLV.

The development of a reusable engine, being of central significance for the operational system, is to be preceded by appropriate ground demonstrators such as the ESA-funded Prometheus demonstrator engine development [39].

Such a publicly funded program will benefit and accompany the industrial development of the operational system. It is clear that with advancing development, more

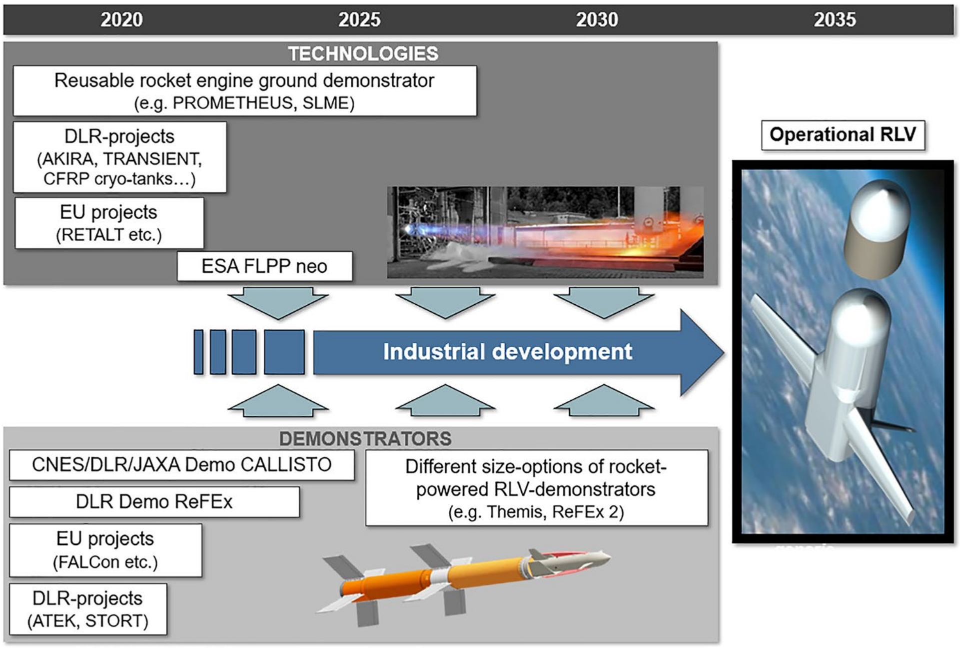


**Fig. 9** Potential roadmap toward an operational European TSTO with a reusable first stage

and more industry involvement is needed for realizing some of the technology and demonstrator development program.

Figure 9 draws a potential roadmap arranging the various development strings currently underway and potential evolutions toward a European operation RLV.

## 6 Conclusion

Europe's access to space currently relies solely on expendable launch systems. In the face of the successful introduction of reusability to the launch services in the United States, the increasing cost pressures and the questions of sustainability challenge any view of pursuing in Europe with expendable launch systems after a future decommissioning of Ariane 6 and Vega. Reusing the first stage is an obvious first but decisive step of introducing reusability to the European launch capability. While it may seem tempting to simply follow the approaches selected by US companies like SpaceX, it may be worthwhile to investigate alternatives prior to committing to a lengthy and costly development program. To this end, DLR initiated a large system study of two-stage-to-orbit heavy launch systems with a reusable first stage with a special focus on the recovery method. The main interest was to compare two entirely different recovery approaches: vertical landing and horizontal landing since the decision for one or the other entails entirely different architectures and would set Europe on diverging technology development paths. These two landing approaches were further diversified by considering specific recovery methods as well leading to two investigated recovery methods for each landing method.

Further key design parameters were identified and included in the concept matrix, such as fuel type and engine cycle. Common fuel types, such as cryogenic fuels (LOX/LH2), methane (LOX/LCH4), and kerosene (LOX/RP-1), were investigated. This was complemented for evaluation purposes by an investigation of propane (LOX/LC3H8). Gas generator cycles, a technology well mastered by Europe since decades, were considered alongside staged combustion cycle engine for which a technology development program would be required.

For each variant, three staging points were fixed based on the propulsive $\Delta V$ delivered by the upper stage. A design loop involving mass estimation, aerodynamic database calculations, coupled trajectory optimization for ascent and re-entry and architectural studies were performed to obtain a convergent design for each variant.

A down-selection process compatible with the preliminary nature of the achieved design level was applied to the variants evaluating the relative performance of each one of them with respect to the selection criteria launch costs, development costs, development risk, growth/shrink potential, mission flexibility, reliability, and environment.

At the outcome of this down-selection process, one set of design parameters for two-stage-to-orbit launch system with a horizontally landing first reusable stage and one for that with a vertically landing first reusable stage were evaluated more favorably than other competing variants. They both have in common to rely on hydrogen fuel that with respect to the selection criteria faire noticeably better than their hydrocarbon-fueled counterparts. While in terms of engine cycle, the gas generator cycle received overall a more favorable compared to staged combustion for the VTVL variants this distinction is less obvious for the VTHL category. For this latter category, the in-air capturing method ranked better than the VTHL concepts relying on fly-back for first stage recovery.

Finally, a possible development roadmap toward a European two-stage-to-orbit launch system was drafted for a commissioning of such a system by the year 2035 based on on-going technology development in Europe.

**Author contributions** I.D. prepared and revised the main manuscript, figures 4 and 5, tables 2 to 6, contributed to formatting of figures 6, 7, 8 and 9 S.S. prepared table 1 and figures 6, 7 (data and python script) and figure 8, contributed to tables 2, 3, 4 and (data) L.B and J.W. contributed to figures 6, 7 and 8 (data), contributed to tables 2, 3, 4 and 5 (data), contributed to sections 3 and 4 M.S. contributed to section 2, 3, 4 and prepared figure 9. S. S. contributed to the data generation on which the figures are based. All authors reviewed the manuscript.

**Funding** Open Access funding enabled and organized by Projekt DEAL.

**Data Availability** Datasets were generated to produce tables and figures in this manuscript. These can be made available on request under compliance to applicable laws.

## Declarations

**Conflict of interest** The authors have no competing interests to declare that are relevant to the content of this article.

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