CEAS Space Journal
https://doi.org/10.1007/s12567-024-00577-5

ORIGINAL PAPER

Options for future European reusable booster stages: evaluation and comparison of VTHL and VTVL costs

Jascha Wilken[1] · Moritz Herberhold[1] · Martin Sippel[1]

Received: 2 September 2024 / Revised: 8 November 2024 / Accepted: 9 November 2024
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Abstract
As the space industry evolves towards more cost-effective solutions, the development of reusable launch vehicles has become a crucial focus for reducing launch costs. This study addresses the problem of identifying the most cost-effective reusable booster stage design for future European launch systems, comparing vertical takeoff, horizontal landing (VTHL) and vertical takeoff, vertical landing (VTVL) methods. Conducted under the ENTRAIN (Europe's NexT Reusable Ariane) study by the German Aerospace Center (DLR), the research provides a detailed analysis of both recurring and non-recurring costs associated with various design configurations. The study explores different design degrees of freedom, including engine cycles, propellant combinations, and staging velocities, using a parametric cost model to evaluate the trade-offs involved in each configuration. Findings indicate that reusable configurations can achieve significant cost reductions across a wide range of market scenarios, and offer slight total cost benefits even for the smallest herein considered launch markets. The results further show that the hydrogen-fueled configurations investigated within ENTRAIN offer lower costs compared to the hydrocarbon-fueled alternatives. In addition, the study highlights the sensitivity of launch costs to factors such as market conditions, reuse cycles, and refurbishment efforts, offering insights for future European space launcher development.

Keywords Reusable launchers (RLV) · VTVL · VTHL · Cost modeling · Launch market uncertainty · Market scenarios

1 Introduction

As the Ariane 6 enters service, the future trajectory of launcher development in Europe remains uncertain. It is increasingly likely that the next major European launcher will incorporate partial reusability. However, when this study was initiated in 2018, several critical aspects of the new launcher architecture, such as vehicle staging, fuel selection, and engine cycle, were still undefined and remain so to this day. While qualitative arguments supporting various options are well established, their quantitative impact on the overall vehicle system and its costs are not fully understood. For instance, while hydrogen is known for its high specific impulse, it also poses challenges due to its extremely low boiling point and low density. Conversely, hydrocarbon fuels, which are denser, result in lower specific impulses.

The quantifiable effects of these competing qualitative factors on launcher performance have not been thoroughly established and may vary significantly across different use cases. Accurately assessing these impacts necessitates a comprehensive, multidisciplinary evaluation of the entire launcher system for each potential option.

The Europe's NexT Reusable ArIaNe (ENTRAIN) study, performed by DLR, aims to fill this gap by providing a quantitative evaluation of options for a partially reusable European launch system, thereby establishing a solid technical foundation for future discussions. Although the study's scope and iterations preclude the use of high-fidelity methods such as computational fluid dynamics (CFD) or finite-element (FE) models, key subdisciplines are modeled using specialized conceptual design tools. For example, the evaluation of each launcher configuration includes structural design analysis, trajectory optimization for both ascent and descent, and modeling of the propellant tank along with associated feed, fill, and pressurization systems.

The study explores a range of design parameters, including staging velocity, fuel choice, engine cycle, and recovery method, to offer a comprehensive understanding of

✉ Jascha Wilken
jascha.wilken@dlr.de

[1] Space Launcher Systems Analysis, Institute of Space Systems, Deutsches Zentrum für Luft- Und Raumfahrt (DLR), Bremen, Germany

Published online: 05 December 2024

the trade-offs and potential advantages of various design choices.

The findings of this extensive study are documented in several publications. Reference [1] offers an overview of the study's methodology and its relation to other European initiatives. Reference [2] focuses on the propulsion datasets and the underlying rocket engine models. In Refs. [3, 4], the technical work done for the VTVL and VTHL stages is described and discussed, respectively. Reference [5] provides an in-depth comparison of different recovery methods.

In these publications, the discussions are limited to the technical data; however, the actual goal of a partially reusable launch vehicle is the reduction of launch cost. While technical data such as dry mass or total mass can be used as surrogates for the cost estimation, this approach neglects aspects influencing the recurring and non-recurring cost of the vehicles.

Within this work, an attempt is made to expand the previously purely technical analyses and to estimate the recurring and non-recurring cost associated with each investigated configuration and compare them to each other.

1.1 Study logic and high-level assumptions

The ENTRAIN study was structured into two parts: the first part concentrates on a comparative analysis of VTVL and VTHL launchers ensuring uniformity in the investigation level to prevent distortions from varied degrees of detail. Therefore, identical high-level requirements and assumptions are used for all configurations:

- 7000 kg + 500 kg margin payload to geostationary transfer orbit (GTO)
- Launch from Centre Spatial Guyanais (CSG), Kourou
- Two stage to orbit (TSTO) configurations
- Same propellant combination in both stages
- Same engines in both stages with exception of different nozzle expansion ratios.

In the VTVL launchers detailed in Ref. [3], an exception to the aforementioned two requirements is included: a hybrid launcher configuration. This unique configuration incorporates a methane-fueled lower stage and a hydrogen-fueled upper stage.

Based on these requirements, the following degrees of freedom were explored:

- Engine cycles: gas generator (GG) and staged combustion (SC)
- Recovery modes:
    - VTVL with retropropulsion landing on downrange barge (DRL)
    - VTHL with in-air-capturing and subsequent towing by a waiting aircraft (IAC)
    - VTHL with return to launch site (flyback) with integrated turbojet engines (FB)
- 2nd-stage Δv: 6.6 km/s, 7.0 km/s and 7.6 km/s
- Propellant combinations:
    - Liquid oxygen (LOX)/liquid hydrogen (LH2)
    - LOX/liquid methane (LCH4)
    - LOX/liquid propane (LC3H8)
    - LOX/kerosene, rocket propellant-1 (RP-1)

In the analysis of the staging variations, the upper stage Δv was chosen instead of the more commonly used separation Mach number, as explained in Ref. [1]. For reference, the upper stage Δv of 6.6 km/s, 7.0 km/s, and 7.6 km/s approximately correspond to a separation Mach numbers of 12, 10 and 7, respectively.

1.2 Why do cost estimation?

Cost estimations are notoriously unreliable in most fields, and especially so in spaceflight. Even the organizations with full access to detailed current cost data have not been able to reliably estimate the time and effort associated with future projects.

Yet, nowadays a desired reduction of cost is the main driver of the development of the next generation of launch vehicles, beyond the baseline goal of independent access to space. When examining the different options for a future European semi-reusable launch vehicle, the associated cost is a necessary part of the whole picture.

For mechanical engineering products, 75% of the manufacturing cost is committed by the decisions made in the conceptual design phase [6]. In these early design phases, especially for new products, the uncertainties of the cost estimation are very high. However, the information is absolutely critical for early decisions that will define a significant portion of the final cost. Therefore, in order to avoid early incorrect decisions, initial estimates are critical, even if their absolute results have to be interpreted with care. In later design phases, while the amount and quality of data is better, core design features are already frozen and only minor changes can be made.

This situation is further complicated by the lack of publicly available cost data. Even for publicly funded launcher systems, the actual recurring and non-recurring costs are often not disclosed. Without reliable cost data and estimations based on them, decision-makers are left to rely on information provided by potentially biased parties. Commercial entities, with a vested interest in promoting their existing portfolios, have little incentive to evaluate what might be the best solution for society, which often funds their development projects.

The authors recognize their own potential biases as well, but hope that this publication can contribute to the ongoing discussion on these issues.

A partial remedy for the uncertainties in the cost estimation is a focus on relative cost comparison, which will be the case for this manuscript. Different future European launcher options are compared and thus, the absolute values are not the core result. Instead, the goal is to gain insights into the relative effect of the design options investigated within ENTRAIN on the total cost.

With this background and the mentioned caveats, herein an attempt is made to estimate the recurring and non-recurring cost of the vehicle concepts investigated within the ENTRAIN study. Section 2 briefly describes the investigated launch vehicles, with a focus on a number of expendable versions. The cost models employed are described in Sect. 3. The results are shown in Sect. 4 and discussed in Sect. 5. The caveats that apply to this analysis are discussed in Sect. 5.1.

2 Reference launchers

2.1 ENTRAIN configurations

A technical description of the VTVL and VTHL launchers and their major subsystems for which the cost estimation is done herein, is given in Refs. [3, 4]. The propulsion datasets are discussed in Ref. [2]. Sketches of some of the investigated launchers are shown in Fig. 1.

2.1.1 Nomenclature

The range of launchers considered in this study is categorized using a nomenclature that makes it easy to distinguish between vehicles based on key design space parameters, as outlined in Table 1. This nomenclature employs simple abbreviations for the return methods and engine cycles. In terms of propellants, each propellant combination is represented by a unique substitute letter. The first stage separation velocity is indicated by terms such as “Hi” for high, “Med” for medium, and “Lo” for low separation velocity.

Table 1 Design matrix of ENTRAIN study with nomenclature abbreviations

Design parameter	Description	Nomenclature
Return method	VTVL downrange landing	DRL
	VTHL in-air-capturing	IAC
	VTHL flyback	FB
	None (ELV)	EL
Propellant	LOx-LH2	H
	LOx-LCH4	C
	LOx-LC3H8	P
	LOx-RP1	K
Engine cycles	Staged combustion	SC
	Gas generator	GG
Upper stage Δv	6.6 km/s	Hi
	7.0 km/s	Med
	7.6 km/s	Lo

For example, a launcher featuring vertical landing with downrange landing, LOX/LH2 in both stages, gas generator engines and an upper stage Δv of 7.0 km/s would be dubbed: *DRL HH GG Med*.

2.2 Expendable variants

To compare the cost of the investigated RLV launchers with that of traditional ELV launchers, five reference ELV configurations are designed. These adhere to the same requirements employed for the partially reusable launchers described in Refs. [3, 4]. This part of the study focuses on

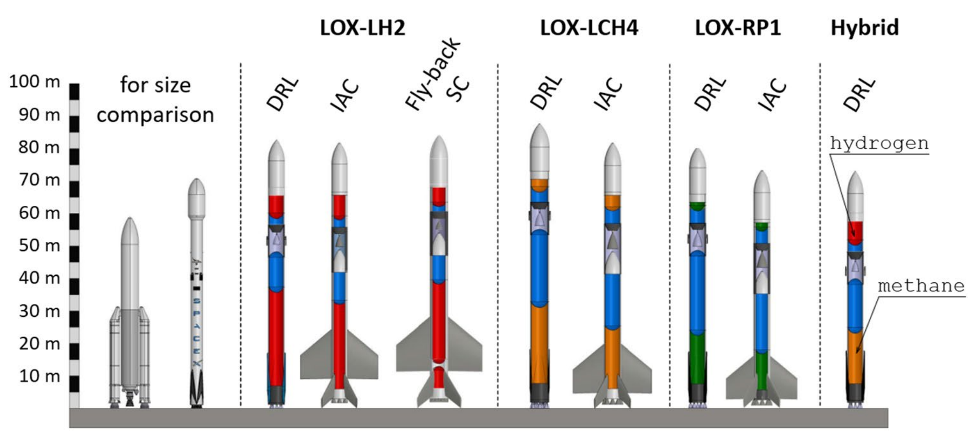

Fig. 1 Sketch of selected launchers investigated within the ENTRAIN study, from Ref. [5]

the LOX/LH2 and LOX/LCH4 propellant combinations and the 7.0 km/s Δv upper stage. Both gas generator engines and staged combustion engines are examined. A hybrid configuration is also investigated. It features LCH4/LOX in the lower stage, and LH2/LOX in the upper stage and uses gas generator engines for both stages. The key parameters of the resulting ELV configurations are shown in Table 3.

Some systems required for recovering the first stage of VTVL configurations are unnecessary in an expendable configuration and are thus excluded from the mass model. These systems are the landing legs, the grid fins, the first stage reaction control engines and their fuel, as well as the insulation protection, and the thermal protection system. Eliminating these components reduces the stage's dry mass. In addition, no fuel must be reserved for the reentry burn and landing burn of the first stage, significantly reducing the required fuel amount. This further reduces the first stage dry mass, as it allows for smaller tanks. The number of first stage engines and the engine mass flow rate are adjusted to maintain an initial thrust-to-weight ratio of 1.4 across all configurations. The engine masses are changed to keep their thrust-to-weight constant at the values specified in Ref. [2]. As shown in Fig. 2, in total, the first stage dry mass of the ELV's first stage is reduced by one-third or more compared to the equivalent VTVL's first stage. A similar effect can be seen for the hydrogen VTHL stages. Only the IAC CC GG Med first stage shows a smaller dry mass difference of 15% to its expendable equivalent. The largest dry mass reduction is seen between DRL CC GG Med configuration and the ELV CC GG Med configuration, as the former uses the largest amount of fuel for its reentry and landing burn. Its dry mass shrinks by 38%.

The second stage's dry mass, also shown in Fig. 2, exhibits only minimal differences between the recovery methods, as all configurations shown use expendable upper stages with 7.0 km/s Δv. The minor variations arise from differing diameters and engine sizes.

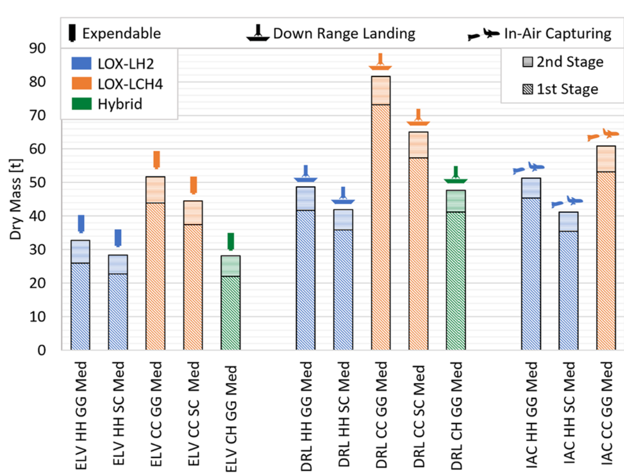

Fig. 2 Dry mass of configurations with different propellant combinations, engine cycles, and first stage recovery methods

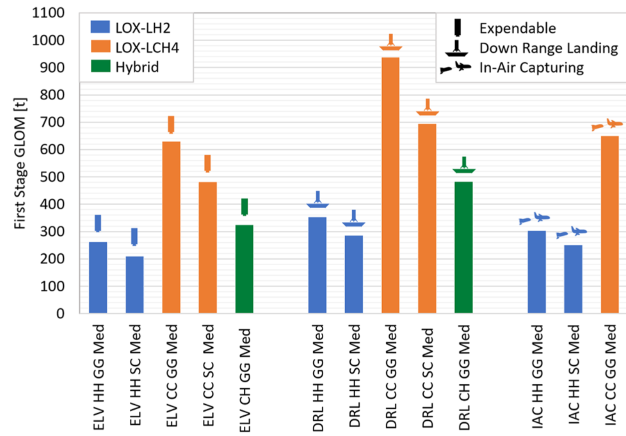

Fig. 3 GLOM of first stages with different propellant combinations, engine cycles, and recovery methods

Figure 3 illustrates a comparison of the Gross-Lift-Off-Masses (GLOM) for the investigated launchers. The difference in dry mass between the ELV and DRL configurations is reflected in the GLOM of both recovery methods. The GLOM of the IAC configurations is only slightly higher than the ELV's GLOM, as the IAC stages require no additional fuel for the recovery. The slight increase can be traced back to the higher dry mass of the winged first stages and the larger amount of fuel needed to accelerate that additional mass. When the GLOM of the ELVs is compared, the general trends previously observed for the RLVs (see Refs. [3, 4]) are retained. The LOX/LH2 configurations remain the smallest and lightest. Using LOX/LCH4 as propellant a configuration with more than twice the GLOM is necessary to accomplish the required GTO mission. The GLOM of the hybrid configuration sits in between, although closer to the LOX/LH2 GLOM. In addition, the use of staged combustion engines over gas generator engines lowers the GLOM by 20% and more.

2.3 Performance for SSO orbits

The transport of 7.5 t into GTO is the dimensioning use case for all configurations, but these missions represent only a portion of the global launch market [7]. To evaluate the economic performance of a launch system, its payload capabilities into Low-Earth-Orbits (LEO) have to be analyzed. However, the LEO group includes a wide range of orbits. These orbits have differing Δv budgets and consequently differing payload performances by the same launch system. The transport of a payload into a high SSO-orbit was chosen to represent this wide range of missions. Such an orbit requires a large Δv budget for a LEO mission, thus representing a conservative estimation of the launcher's LEO performance [8].

The exact orbit chosen is a circular 800 km orbit with an inclination of 98.6°. The designated launch site is the CSG in Kourou French Guiana. The orbit is reached by an initial ascent into 200 × 800 km orbit and a later recircularization maneuver without inclination change. The upper stage's main engine is relit for the recircularization. The fuel allocated to the engine's relight and chill down is assumed to be equivalent to the amount consumed by the upper stage during 2 s of full thrust. A direct ascent into a circular 800 km SSO orbit was also considered but found to be less efficient. For the VTVL configurations, both the down range landing (DRL) as well as return to launch site (RTLS) were investigated. The VTHL configurations all use the in-air capturing (IAC) recovery.

The SSO performance of the configurations is shown in Table 4. The LCH4/LOX GG configurations achieve with 18 t the highest payload to SSO, followed by the LCH4/LOX SC configurations with payloads around 17 t. The LH2/LOX configurations achieve lower payloads of 14.5 t for the GG engines and 13.5 t for the SC engines. The hybrid configurations also achieve payloads of 14.5 t. The configurations with the same engine and fuel combination achieve similar payloads, independent of their recovery method. The primary factor influencing the SSO payload appears to be the ISP of the upper stage, with lower ISPs resulting in higher SSO payloads. Launching into SSO requires a lower Δv budget than the dimensioning launch into GTO. The lower the ISP of the upper stage, the larger the fuel mass fraction needed to achieve the Δv difference between a launch into SSO and GTO. Consequently, for a launch into SSO a configuration with lower ISP has a larger fuel mass fraction available to carry additional payload. This results in larger payloads into SSO for the configurations with less efficient upper stages.

The SSO payload was not evaluated for all launchers. It was assumed that the results from the medium stage separation velocity cases are transferable to the other staging velocities and that the results from the methane-fueled launchers are representative for all hydrocarbon-fueled launchers.

For the VTVL configurations the SSO payload with first stage RTLS is also investigated. The resulting SSO payloads, detailed in Fig. 4, are all close to 10 tons, showing minimal variations between different engine and fuel types.

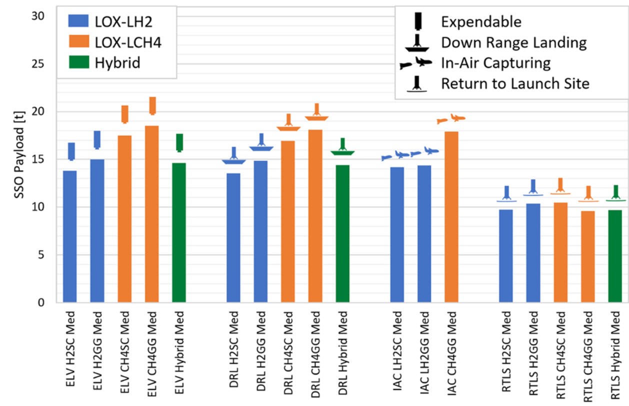

Fig. 4 SSO payload with different propellant combinations, engine cycles, and recovery methods. For the VTVL launchers, both DRL and RTLS payload performance is given

3 Cost modeling

Generally, the cost of a launch vehicle in its various development stages can be estimated by one of five methods [9]:

- Engineering bottom-up
- Analogy estimation
- Parametric cost estimations
- Expert judgment
- Rough order of magnitude estimation.

The differences between the ENTRAIN configurations were expected to be too small to get useful results from the order of magnitude estimation. Similarly, relying on analogies for the entire system would likely not be able to account for smaller differences within the design space. Ideally, an engineering bottom-up model would be generated for each configuration. However, this requires sufficiently detailed designs so that the cost of each subsystem and component can be assessed. In this study, only major subsystem masses are available, not the technical details of every component. Instead, a parametric cost model with a focus on selected major subcomponents is employed. This allows the direct use of the technical data generated within ENTRAIN while allowing adjustments to be made for the individual design features. The caveats associated with this methodology are discussed in Sect. 5.1.

Specifically, this study utilizes the TRANSCOST parametric cost model [10], with adaptations similar to the approach used in Ref. [11]. The TRANSCOST model, developed by D. Koelle, employs a top-down approach, estimating costs at the system level using Work-Year (WYr) units. This method allows for inflation-excluded cost comparisons across different time periods. Launch vehicle costs are calculated using cost estimation relationships (CERs) derived from historical data through regression analysis on the basic exponential equation (Eq. 1). Component categories include, for example, liquid stages, solid stages, pressure-fed engines, and turbopump-fed engines. In this case, the reusable first stages were further divided in landing, reentry, interstage and core stage components:

$$E = a \cdot M^x \quad (1)$$

Factors such as system complexity, team experience, and technology readiness (TRL) are introduced into Eq. (1) for specific cost types.

Hereafter, a work-year cost of 370 k€ is assumed. This results from extrapolating the WYr cost data for Europe from TRANSCOST to the year 2022.

The following sections discuss the specific CER's chosen for each component as well as the fuel or engine-specific adaptations of the coefficients used in the CER's. The values of all coefficients used are given in Table 5 in the appendix. Unless specified, coefficients default to a baseline value of 1. For instance, the team experience factor f_3 is set at 1 to ensure comparability, as no specific entity for launcher implementation is defined.

As the ground infrastructure was not assessed during the technical analysis of the ENTRAIN study, the investment necessary for infrastructure build-up is not included in this cost analysis. The recurring cost associated with vehicle ground operations is modeled according to TRANSCOST.

3.1 Distortion introduced by relying on dry mass-based CERs

The models discussed in this chapter primarily focus on CERs based on the dry mass of components, which may lead to distortions when considered from the perspective of other relevant metrics.

For instance, rocket engines are typically evaluated based on their thrust class rather than dry mass. Comparing engines with equivalent thrust is more informative than comparing those with the same dry mass. For example, the thrust-to-weight (T/W) ratio for a methane-fueled gas generator engine is estimated at 105, whereas it is 75 for its staged combustion cycle counterpart (from [2]). Consequently, the dry mass relative to thrust level is approximately 31% greater for the staged combustion engine. Thus, despite using the same mass-based CER for both engines, the cost comparison changes significantly when thrust levels are considered. The staged combustion engines appear notably more expensive. The impact on costs varies depending on the exponent applied in the CER calculations. In this case, an exponent of 0.48 is used, indicating that the increased dry mass corresponds to an approximate 14% higher development cost for a staged combustion engine with the same thrust level, before any adjustment to the coefficients.

Similarly, when comparing stages with identical propellant loading, the structural index of the various design options results in different cost per propellant loading if the cost per dry mass is assumed to be identical. Assuming, for example, that a reference expendable hydrogen-fueled stage has a structural index of 9% and methane-fueled stage with the same propellant loading has a structural index of 5%, this results in the production cost of the methane stage being 26% lower than a hydrogen-fueled stage with same propellant loading (including the effect of the production CER exponent).

The focus on dry mass as a primary cost driver in the development and production of components is justified, given its substantial influence on expenses. However, it is crucial to acknowledge the potential distortions this focus may introduce when applying CERs. To ensure that the CERs align with the intended modeling assumptions, it is essential to carefully select and adjust the coefficients and be aware of the distortions already inherent in use of dry mass as the scaling parameter.

3.2 Non-recurring costs

The development cost for a single component is calculated as

$$E_{\mathrm{dev}} = f_1 \cdot f_2 \cdot f_3 \cdot a_{\mathrm{dev}} \cdot M^{x_{\mathrm{dev}}} \tag{2}$$

Here, f_1 reflects technological readiness and complexity, f_2 is a technical quality factor, and f_3 represents team experience. The system engineering and integration effort (E_{sys}) of an entire launch vehicle with i components is calculated as

$$E_{\mathrm{sys}} = \left(1.04^N - 1\right) \cdot \sum_{1}^{i} E_{\mathrm{dev},i}$$

Here, N is the number of stages.

3.2.1 Core stage

The core stage component consists of all elements classically found on expendable launch vehicles for which historical data exist. For the development effort of the core stage itself, the updated CER from Ref. [12] was used.

The f_1 factor of all expendable stages is set to 0.7, to reflect that expendable cryogenic stages are state-of-the-art.

3.2.2 Reentry and landing hardware

The CER's based on historical stages do not include landing and reentry hardware, as the underlying stages were expendable. Depending on the recovery mode in question, the landing components consist of the landing gears or landing legs. Similarly, the reentry component can include either wings, grid fins or the thermal protection system. For the development effort of the landing and reentry hardware component, the cost estimations of the FESTIP studies [13] were used as the basis to generate specific CER's for these components. The resulting coefficients are given in the Appendix in Table 5.

3.2.3 Interstages

The interstages are modeled as separate components because they are jettisoned for the winged configurations in order expose the aerodynamically more efficient nose, as can be seen in Fig. 1, and thus can't be considered part of the reusable first stage. The development effort for an interstage is estimated via a linear scaling with regard to the component mass based on the values given in Ref. [14] for the development of a sandwich-based interstage for the ARES-V launcher concept by NASA.

3.2.4 Propulsion

For the rocket propulsion elements, the CER's from TRANSCOST for modern pump fed engines were used for estimation of the development effort. In order to reflect the smaller European heritage of hydrocarbon-fueled engines, the f_1 factor is increased by 10%, while it is kept at 1 for hydrogen-fueled engines. f_1 is also increased by a further 10% for all closed-cycle engines, in addition to the implicit bias discuss above, this results in the development of staged combustion engine being ~ 25% more expensive than the development of an equal thrust gas generator cycle engine. For the recurring cost, the difference is ~ 15%.

For the airbreathing engines used in the FB cases, the effort assessed within the ASTRA [15] study was used. The same engines (EJ2000) are assumed therein and for the ENTRAIN FB configurations. As these engines already exist, only modifications to the design for the operation on hydrogen as the fuel are considered.

3.2.5 Guidance, navigation and control of reusable stages

Finally, a dedicated fixed cost component for the development of the guidance, navigation and control (GNC) systems necessary to safely decelerate and return the stages after separation is included. For the three recovery modes DRL, IAC and FB 2500, 2000 and 2200 WYr were budgeted for this effort. These values are rough assumptions and try to represent that for VTVL both propulsion and aerodynamic systems have to be mastered and that the flyback return mode includes the additional powered subsonic flight mode that also has to be included. No recurring costs are foreseen for this component, as the core stage already includes the mass of the electrical systems needed to execute the GNC algorithms.

3.3 Recurring costs

Recurring costs include production effort, prelaunch ground operations, and system costs. Production cost is calculated as

$$E_{\text{prod}} = f_4 \cdot a_{\text{prod}} \cdot M^{x_{\text{prod}}} \tag{4}$$

Here, f_4 accounts for cost reduction through series production, based on a learning factor p and production number n:

$$f_4(n) = n^{\frac{\ln p}{\ln 2}} \tag{5}$$

The effort for refurbishing a component is modeled as a fraction f_5 of the theoretical first unit (TFU) cost of the component:

$$E_{\text{prod,TFU}} = a_{\text{prod}} \cdot M^{x_{\text{prod}}} \tag{6}$$

$$E_{\text{refurb}} = f_{4,\text{refurb}} \cdot f_5 \cdot a_{\text{prod}} \cdot M^{x_{\text{prod}}} \tag{7}$$

As for the production cost, a learning effect which reduces the costs depending on the number of previously refurbished stages m is employed. The cost reduction, given in Eq. (8), is calculated similarly to Eq. (5), only with a specific p_{refurb} for this aspect. The learning factors for both the production and the refurbishment are assumed to be 0.85:

$$f_{4,\text{refurb}}(m) = m^{\frac{\ln p_{\text{refurb}}}{\ln 2}} \tag{8}$$

The effort of recovery of the stages is based on the analysis in Ref. [16]. Corrected for the herein assumed WYR cost of 370 k€, this results in a fixed recovery cost of ~ 850 k€ for DRL and IAC and ~ 310 k€ for the RTLS recovery. No scaling with dry mass of the returned stage is done here, as the infrastructure assumed in the derivation of these values is sufficient to handle the launchers of the size encountered within ENTRAIN.

3.3.1 Core stage

The core stage component consists of all elements classically found on expendable launch vehicles for which historical data exist. For the production effort, the original CER from TRANSCOST is used.

The main parameters governing the recurring cost of reusing a stage are the number of reuses and the refurbishment factor f_5. To be competitive with VTVL stages, vehicles using VTHL technology must achieve a greater number of reuses while requiring less refurbishment effort. The baseline assumption for winged reusable stages is set at 50 reuses with a refurbishment factor of 2.3%, a figure derived from the Space Shuttle's historical data [10]. In contrast, VTVL stages are assumed to have a refurbishment factor of 5% and 25 reuses. Although specific values for the Falcon 9 are not available, as of 2020, the refurbishment and recovery costs were projected to be less than 10% of the new launcher production costs, as noted in [17]. While 25 reuses have not achieved at this moment, it appears to be simply a matter of time until this is the case.

Given the inherent uncertainties in all these parameters, their impact is further explored through a parametric variation study detailed in Sect. 4.3.

3.3.2 Reentry and landing hardware

Just as for the development cost, as discussed in Sect. 3.2.2, for the production of the landing and reentry component, the cost estimations of the FESTIP studies [13] were used as the basis to generate specific CER's for these components. The resulting coefficients are given in the Appendix in Table 5.

The refurbishment factor and number of reuses are set to the same value as the for the core stage, discussed in Sect. 3.3.1.

3.3.3 Interstages

The interstages are modeled as separate components because they are jettisoned for the winged configurations in order expose the aerodynamically more efficient nose and thus cannot be considered part of the reusable first stage. The production effort for an interstage is estimated via a linear scaling with regard to the component mass based on the values given in Ref. [14] for the production of a sandwich-based interstage for the ARES-V launcher concept by NASA. Where applicable, the refurbishment factor and number of reuses are set to the same value as the for the core stage, discussed in 3.3.1.

3.3.4 Propulsion

For the propulsion elements, the CERs from TRANSCOST for modern pump fed engines were used for estimation of the production effort.

It is assumed that hydrocarbon-fueled engines have production costs approximately 30% lower per unit of thrust than hydrogen-fueled engines. One reason for this is the additional effort necessary for production of the complex hydrogen turbopump, while the hydrocarbon-fueled engines can be operated with a single turbine for both the fuel and oxidizer pumps. As the TRANSCOST model does not foresee a specific calibration factor for the production effort, a_{prod} for the hydrogen-fueled engines is set to ~ 140% of the values suggested for modern pump fed engines in TRANSCOST. Together with the implicit bias caused by the higher T/W of hydrocarbon engines, this results in a ~ 30% lower recurring cost for the hydrocarbon-fueled engines.

With regard to the reuse, the following assumptions are made: 20 reuses for engines on VTVL stages and 25 for those on winged stages, with refurbishment factors set at 7% and 4%, respectively. The higher refurbishment requirement for VTVL stages accounts for the additional stresses—such as significant aerodynamic heat loads during reentry and multiple ignitions throughout a mission—that these engines endure. Given the inherent uncertainties in all these parameters, their impact is further explored through a parametric variation study detailed in Sect. 4.3.

For the airbreathing engines used in the FB configurations, the effort assessed within the ASTRA [15] study for production was used. The same engines (EJ2000) are assumed therein and for the ENTRAIN Flyback configurations. With regard to reuses, it is assumed that the engines are reused as often as the airframe into which they are integrated (50 times) and that no refurbishment between flights is necessary.

3.4 Evaluation of uncertain launch markets

In order to gain a complete picture of the cost associated with a given launch vehicle both the recurring and the non-recurring costs have to be considered. Obviously, the recurring cost depends heavily on the number of launches considered. Even the average cost of vehicle elements varies with the total number of produced elements, due to the learning factor considered.

In Ref. [11] a methodology was established that allows the consideration of uncertain market scenarios and includes a combinatorial optimization of the payloads onto the available launch options for minimal launch costs. While originally developed for the assessment of launch vehicles families, it is herein applied to the single launchers, essentially modeled as launch vehicles families with a single member. For the VTVL launchers, however, the single launcher offers different operational modes (DRL and RTLS), so in their case the family actually consists of the two variants.

3.4.1 Definition of launch market scenarios

Herein, a launch market scenario is defined by the following key characteristics:

- **Duration of scenario:** Reflecting the long lifespan of launch systems due to significant initial investments, the timeframe for assessing future launch needs is extensive. Longer durations introduce greater market uncertainties.
- **Probability of dedicated launch:** This factor considers the likelihood that a payload requires a dedicated launch due to specific needs such as security concerns, unique orbital requirements, or strict schedules.
- **Market share:** This denotes the percentage of payloads an organization successfully acquires in the competitive launch market. Herein, the market share for single payloads and for constellation payloads are varied separately.

- **Number of launch epochs:** Launch epochs model the intervals between launches to determine payload grouping for rideshare opportunities. Payloads are assigned to epochs randomly, affecting the feasibility of combining them in shared launches based on their time sensitivity.
- **Number and mass distribution of payloads:** Payloads are categorized by their intended orbits, such as Sun synchronous orbit (SSO) and geostationary transfer orbit (GTO). This classification influences the launcher's performance and the potential for rideshare missions, dictated by the compatibility of destination orbits.

Each scenario involves a randomly sampled set of payloads, each defined by mass, destination orbit, and the necessity for a dedicated launch. This structured approach allows for realistic simulation and analysis of market scenarios under varying conditions of uncertainty.

Herein, only GTO and SSO are considered as orbital destinations. Historically, these have been primary targets for non-constellation payloads and are likely to remain important due to their unique characteristics.

Table 2 Uncertainty parameters of launch scenario, all sampled uniformly

Parameter	Interval	Unit
No. of payloads for GTO per year	[7, 13]	–
No. of payloads for SSO per year	[11, 20]	–
No. of constellation payloads	[3000, 5000]	–
No. of epochs	[10, 80]	–
Dedicated launch probability	[0, 0.8]	–
Market share	[0.1, 1.0]	–
Payload mass GTO payload	[2500, 7000]	kg
Payload mass SSO payload	[300, 6500]	kg
Payload mass of constellation payloads	[400, 600]	kg

For constellation payloads, which are anticipated to form a large part of the future launch market, the specific orbital destination is often not fixed, and parameters can vary across the constellation. Due to the lack of comprehensive launcher performance data for all possible inclinations, SSO performance metrics are applied when assigning constellation payloads to launchers.

3.4.2 Uncertainties in future market scenarios

For the forthcoming results shown in Sect. 4, Table 2 outlines the parameter space for sampling individual scenarios, assuming a uniform distribution within defined intervals. These parameters, including the number of payloads and their masses for GTO and SSO orbits, are derived from 2023 ESA forecasts [18], considering only payloads accessible to a European launch provider. The maximum GTO payload mass is limited to 7 t, as this was the design target for the ENTRAIN study. An arbitrary uncertainty of approximately ± 30% is assumed for payload numbers.

The parameters for the number of launch epochs, dedicated launch probability, and market share are designed to explore a broad range of possible future market conditions. The scenarios span 20 years, segmented into launch epochs ranging from a minimum of 3 months to a maximum of 2 years.

4 Results

This section includes the results of all vehicles subjected to the cost estimation methodology described in Sect. 3.

4.1 Results for all configurations

Figure 5 gives an overview over the cost estimation results. The magnitude of the total cost is substantial, but it has to be seen in context of the underlying launch scenarios. The

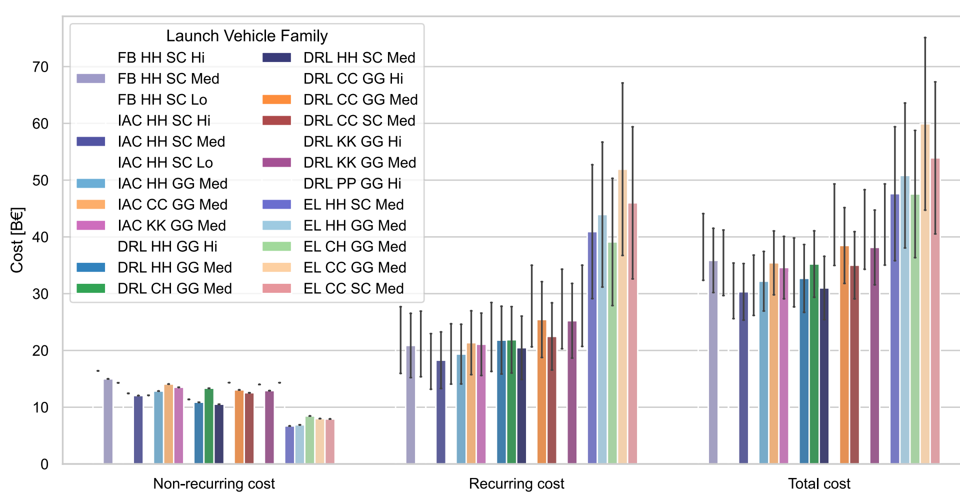

Fig. 5 Results overview all ENTRAIN configurations. The error bars indicate one standard deviation. As only uncertainties in the launch market are considered, the non-recurring cost does not show any variability. (e.c. 2022)

number of launches varies an order of magnitude ranging from 51 to 723 launches, corresponding to ~ 2.6 to ~ 36 launchers per year. Accordingly, there also is a significant spread in the total cost associated with each launcher. In most cases, the recurring cost is much larger than the non-recurring cost, especially for the fully expendable versions. It is noteworthy that under these assumptions, the ELV launchers are always costlier than their equivalent cousins, even in cases where the market share is small.

A more detailed breakdown of the development cost for each configuration is shown in Fig. 6.

The winged stages exhibit higher development cost than the equivalent DRL stages, even though their propellant loadings are smaller (as they do not require propellant for deceleration during reentry). This difference is driven by the higher mass of the reentry components and the associated costs. For the hybrid launchers, the impact of the additional engine development program on the development cost can also be clearly seen.

Figure 7 shows the average recurring launch cost of all configurations, which again puts the large total cost into perspective: per launch, the estimated costs of the configuration with a reusable first stage are lower than most currently operational systems.

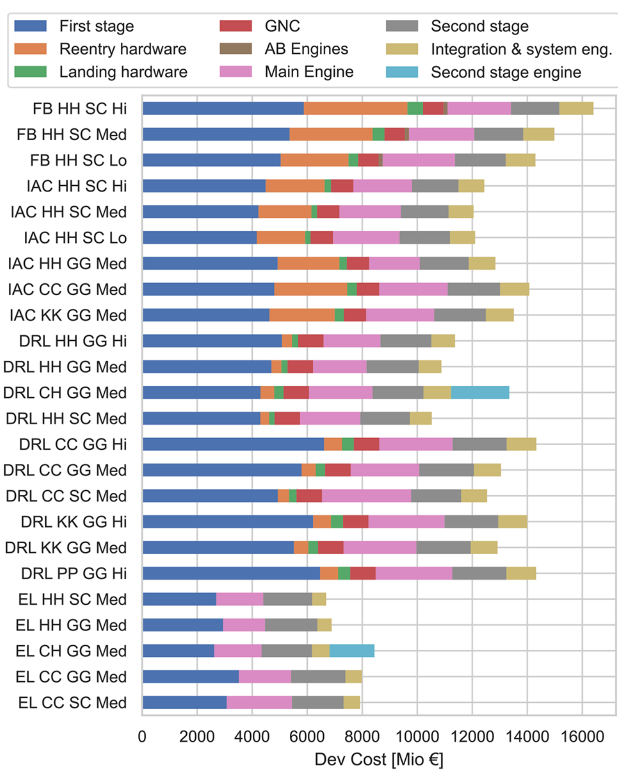

Fig. 6 Development cost breakdown of the launch vehicles investigated within the ENTRAIN study. (e.c. 2022)

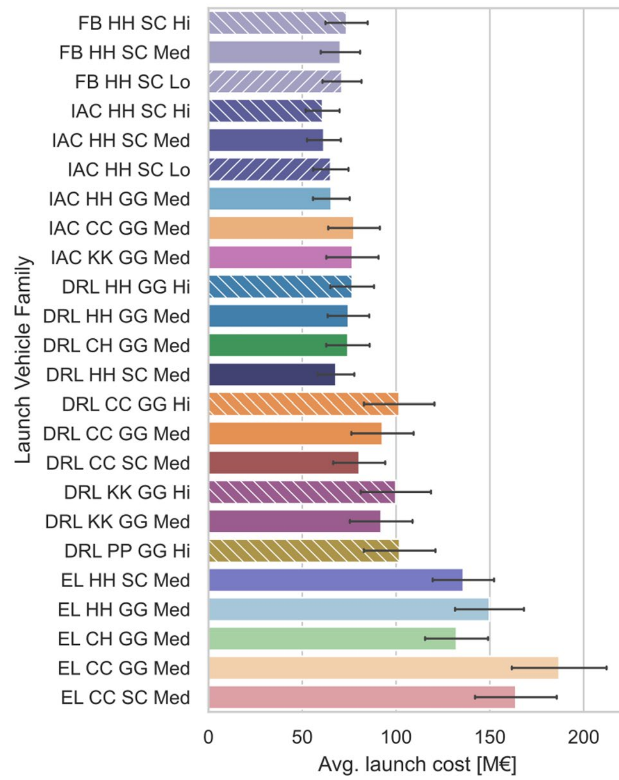

Fig. 7 Average launch cost of the launch vehicles investigated within the ENTRAIN study. The error bars indicate one standard deviation. (e.c. 2022)

For the cases with a reusable first stage, the recurring cost of the first stage is significantly lower than the recurring cost associated with the second stage. Thus, an increase of reuses or reduction of refurbishment cost will not have a major impact in the total cost. Increase of the efficiency of all components and full reusability are the major pathways to reduce the cost significantly further.

4.2 Sensitivity to market scenario

For the sake of clarity in this section, and the next, only selected configurations will be shown and discussed. Methane- and hydrogen-fueled variants are selected with a focus on gas generator engines, as these are the development programs currently underway in Europe for large rocket engines.

In Fig. 8, the effect of the launch market uncertainties on the total cost for all assessed samples is shown. The resulting total cost for all 5000 samples is plotted over the four core uncertainties: Market share in individual payloads, market share for constellation payloads, share of payloads requiring a dedicated launch and the number of launch epochs. The rolling average is indicated by a solid line.

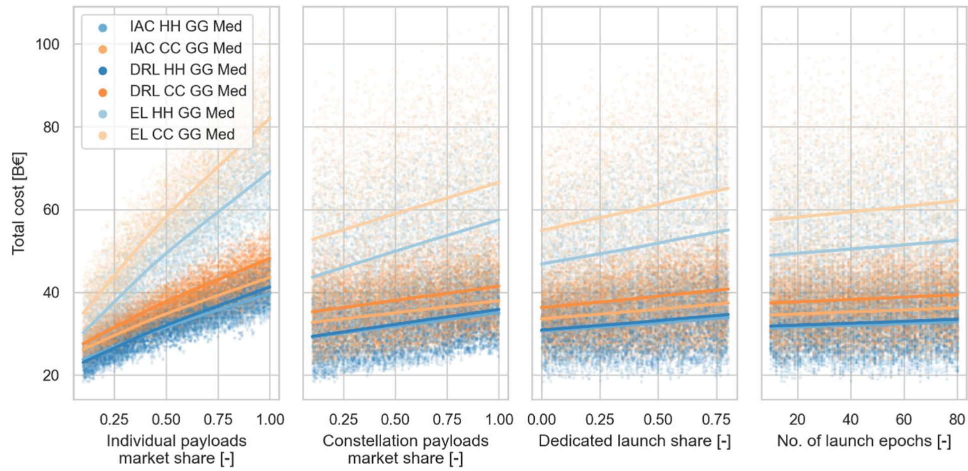

Fig. 8 Sensitivity to uncertain launch market parameters of selected ENTRAIN launchers. 5000 market scenario samples shown. (e.c. 2022)

As expected, the fully expendable variants fare worse, the larger the market share becomes. The IAC configurations exhibit a slightly shallower increase of cost with rising market share, due to the higher number of reuses and lower refurbishment factor assumed for them. For methane-fueled cases, the IAC option always is less expensive than the equivalent DRL launcher. In contrast, for the hydrogen-fueled versions, the comparison is very close, with a slight advantage for the VTVL configuration at lower market shares and vice versa at higher market shares.

The impact of the SSO payload capacity can be seen in the cost increase resulting from an increasing share of the constellation market. The methane-fueled launchers, with their higher SSO payload performance, as described in Sect. 2.3, have a slightly lower sensitivity towards this parameter.

In general, the sensitivity of the results towards the number of dedicated launches and the number of launch epochs is minor. As expected the fully expendable launchers are affected slightly more by the additional launches resulting from increased values of these parameters.

4.3 Sensitivity to parameters associated with reusability

Figure 9 shows the dependence of the total and recurring cost on the number of reuses and the refurbishment factor of the first stage and Fig. 10 shows the same parametric variation but for the engine reuses and refurbishment.

The parameters not being varied are kept at their reference values, as described in Sect. 3.3. Initially, increasing the number of reuses strongly impacts the total cost, however the effect flattens out after ~ 20 reuses for both engines and stages.

As discussed in Sect. 3.2.1, the IAC stages are required to have lower refurbishment factors and a higher number of reuses to be competitive with their DRL equivalents. The results here essentially show the case if only one of these requirements is met, and in the other parameter, only parity is achieved.

For the engine reuses, the effect does not change the overall conclusions. However, for the stage itself, parity in either the number of reuses or the refurbishment factor lead to the hydrogen-fueled VL configuration being less costly than its IAC equivalent. This is not the case for the methane-fueled versions.

These parameter studies indicate that even with only one reuse of the stage the variants with IAC or DRL booster stages have similar costs than the ELV variants. However, this cost parity is due to the fact that engine reuse remains unaffected by this parameter variation. In the absence of these cost savings, an RLV with only a single reuse would naturally be significantly more expensive than its ELV counterpart.

5 Discussion

After a discussion of the study limitations in Sect. 5.1 and a comparison to real launchers in Sect. 5.2, the rest of the discussion is structured around the design degrees of freedom investigated within the ENTRAIN study: engine cycle, recovery mode, propellant and staging velocity. While some differences are small, others are significant enough that conclusions can be drawn with reasonable confidence, despite the uncertainties involved in the process.

5.1 Limitations

From a technical perspective, the uncertainties in the design of the launch vehicles, as discussed in Refs. [3, 4], apply

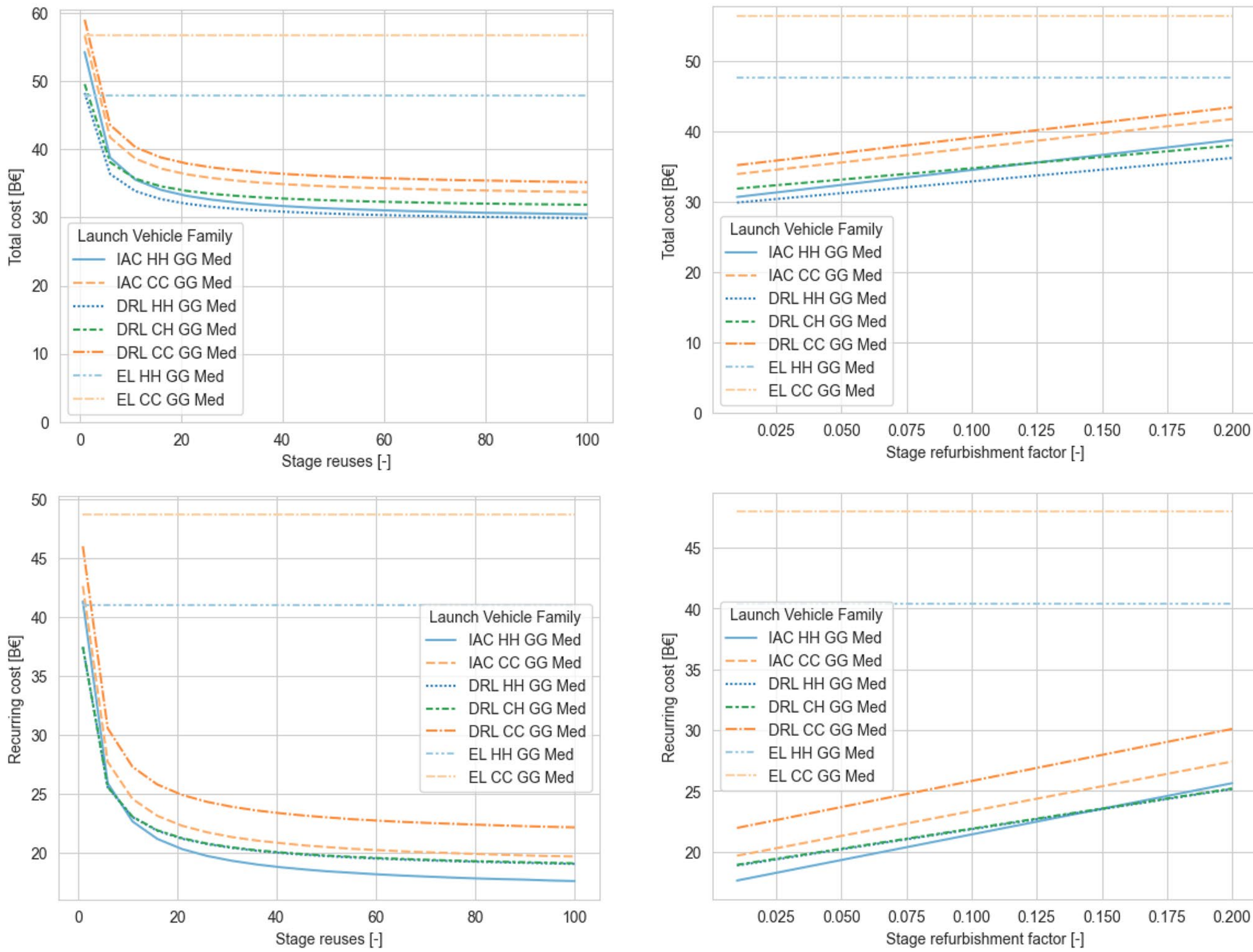

Fig. 9 Effect of stage reuse number and refurbishment factor on total and recurring cost of selected configurations. Average cost from 280 market scenario samples shown. (e.c. 2022)

here as well, since these launchers serve as input for the calculations herein. These uncertainties include potential errors in estimating subsystem masses and performance, as well as inaccuracies arising from the convergence limits of the iterative design process. Generally, the authors consider the uncertainties in the technical parameters as significantly smaller than the uncertainty in the absolute cost estimation.

5.1.1 Parametric cost modeling

In general, boiling down the cost estimation of such a complex project as the development and operation of a launch vehicle over decades to a handful of regression formulas necessarily neglects much of the details involved in the process. However, at the conceptual stage, these details are not available and thus a simplified assessment is necessary. For the relative comparison central to this work, accurately identifying the general cost drivers is essential, whereas precision in estimating absolute values is less critical.

5.1.1.1 Data basis The data used for the formulation of the CERs do not include the most modern launch vehicles, as their cost is usually not publicly known. Even for publicly funded development programs, the final effort is often not trivially available. Also, for the type of stages proposed within the ENTRAIN study, either no previously built stages exist (for the HL configurations) or very limited data is available for the few examples that have been flown (VL). For the CER's used for modeling of the landing and reentry hardware, the results of previous European studies are used, as described in Sect. 3. While these are the results of comparatively detailed cost breakdowns, actual data from operational vehicles would be preferable.

5.1.1.2 Choice of coefficients The selection of specific cost modeling parameters and scenarios reflects certain assumptions made by the authors. These choices, while made to the best of the author's knowledge, may introduce biases that favor certain configurations over others, poten-

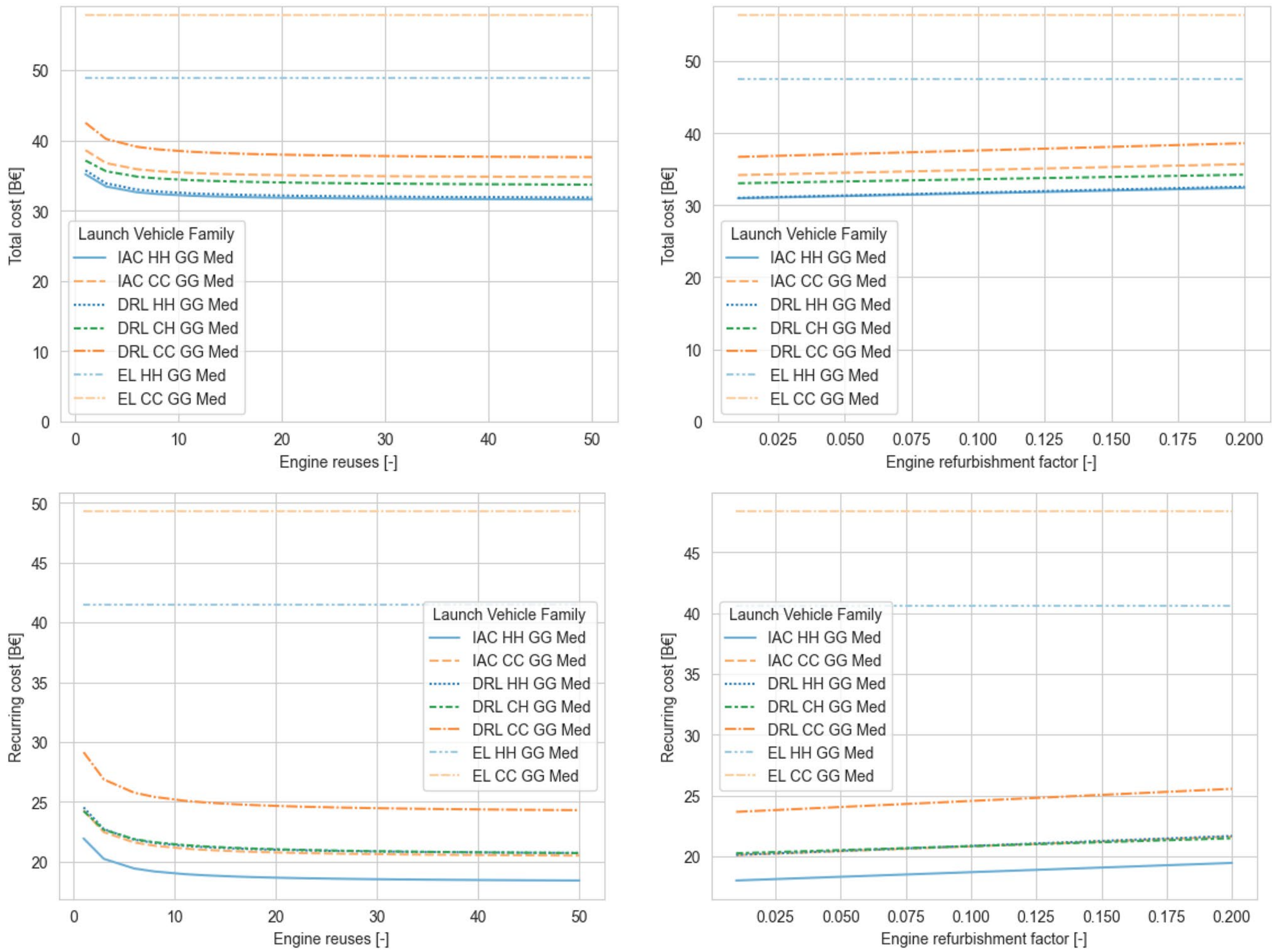

Fig. 10 Effect of engine reuse number and refurbishment factor on total and recurring cost of selected configurations. Average cost from 280 market scenario samples shown. (e.c. 2022)

tially influencing the study's conclusions. For the most uncertain parameters, the ones involving the cost of reusing a stage, a parametric variation was done and presented in Sect. 4.3 to illustrate scenarios beyond the reference assumptions.

5.1.2 Future launch markets

The launch markets considered, as shown in Sect. 3.4.2, span a substantial range, essentially covering an order of magnitude from 2.6 to 36 launches a year over 20 years. The different uncertainties cover a large possibility space. However, as with any prediction of the future, the actual launch market of the future might very well be different from what is expected. Since all these launch vehicles exhibit similar GTO payload capacities, changes in the SSO market are more likely to cause significant distortions. For instance, hydrocarbon-fueled launchers have higher payload capacities for SSO orbits, so if the number of these payloads in the scenario increases significantly, their relative standing might improve, and conversely, it could decline if the number decreases.

5.2 Comparison with current launchers

5.2.1 Falcon 9

As SpaceX currently operates the only partially reusable launch vehicle, the Falcon 9, a comparison comes naturally. While SpaceX publishes prices [19] (currently 69.75 M$), these of course are not identical to actual cost incurred. Currently, the internal cost of SpaceX is speculated to be between 20 M$ and 30 M$ [20]. This is significantly lower than the average launch cost of the DRL KK GG Med configuration in the scenarios with the most launches (~ 66 M€). Multiple factors contribute to this:

- Payload capacity: The Falcon 9 can deliver 5.5 tons to GTO, compared to the 7.5-ton target for the ENTRAIN configurations.
- Low dry mass: The Falcon 9 uses technologies such as propellant densification and structures made of aluminum lithium that enable much lower low dry mass than estimated for the ENTRAIN configurations. The T/W ratio of the Merlin engine is also much higher than assumed for the kerosene fueled engines herein (as discussed in [2])
- Higher launch cadence: SpaceX's launch rate is currently about three times as high as the most optimistic launch market scenarios considered herein (~ 36 launches per year vs ~ 100 launches per year).
- CER data basis: The CERs used in this analysis are based on historical vehicles produced through government contracting, rather than the commercial approach used by SpaceX.

Taking these factors into account, the estimated recurring costs are in reasonable agreement with the real-world data currently available.

The non-recurring cost of the Falcon 9 is not directly comparable, as its design underwent continuous improvement, contrasting with the linear development programs traditionally used for launch vehicles. This continuous development approach differs from the assumptions underlying the CERs used in this study and the historical data they are based on.

5.2.2 Ariane 6

The development of the Ariane 6 has cost more than 4 B€ (mixed e.c.) [21]. This figure excludes the development of new rocket engines, as both the Vulcain and Vinci engines were previously developed and only adapted for this launcher. In addition, the development of the solid booster P120C is not included in these costs. The EL HH GG Med configuration within the ENTRAIN class is likely the most comparable launcher, with an estimated development cost of approximately €6.9 billion (2022 e.c.), which includes the development of a new main rocket engine. While the Ariane 6 boasts a higher payload capacity, its cryogenic stages are actually smaller, with propellant loadings of 140 tons and 31 tons compared to 230 tons and 75 tons for the ENTRAIN configuration. This comparison suggests that the estimated development costs for the most similar ENTRAIN launcher align reasonably with the costs observed in the Ariane 6 development program.

5.3 Comparison of different engine cycles

Although, as discussed in Sect. 3.2.4, the chosen cost modeling approach leads to a 15% higher recurring cost and a 25% higher non-recurring cost per unit of thrust for staged combustion engines relative to their gas generator counterparts, the total cost results suggest that this premium is justified. Configurations with staged combustion engines consistently achieve approximately 6% lower total costs when fueled with hydrogen and 12% when fueled with methane.

The higher specific impulse of closed-cycle engines results in smaller launchers, particularly for the Δv-intensive VTVL stages, leading to overall cost reductions. This benefit extends to all components, including a reduction in thrust requirements, which compensates for much of the higher thrust-specific cost. Consequently, even the recurring engine costs are comparable between the two engine cycle options.

5.4 Comparison of different recovery modes

The comparison between different recovery modes is perhaps the most uncertain aspect discussed herein. No HL first stages have ever been operational for orbital missions, and only one operational launcher currently utilizes a VL first stage. Moreover, the actual costs associated with stage reuse in this case are not publicly available.

The difference between the IAC and DRL configurations largely depends on the specific impulse of the systems. For hydrogen-fueled configurations, the IAC return method has a slight total cost advantage (~ 2%) owing to its reduced recurring costs (~ 12% lower). However, this advantage is mostly offset by higher development costs (~ 14% higher).

For hydrocarbon-fueled configurations, the difference is more pronounced due to the impact of lower specific impulse on DRL vehicles and their larger total Δv budget. The recurring costs for IAC stages are about 19% lower, while the non-recurring costs are about 6% higher, resulting in an average total cost reduction of 9%.

Due to the higher assumed number of reuses and lower refurbishment factors (discussed in in Sect. 3.3.1), IAC stages perform better in launch market scenarios with higher launch frequencies. However, the parametric studies in Sect. 4.3 demonstrated that merely achieving parity in even one of these requirements leads to higher total costs for IAC designs compared to hydrogen-fueled DRL stages. For methane-fueled versions, however, the advantage of IAC stages is more robust, given the greater impact of the lower specific impulse.

With regard to the flyback configurations, they are always costlier than the equivalent IAC options with the difference in total cost increasing from 11 to 20% with increasing separation velocities.

5.5 Comparison of reusable and expendable launchers

As small as the differences are between the various RLV options, the difference towards the fully expendable launch vehicles is significant. The fully expendable launch vehicles are, on average, 36–41% more expensive than their equivalents with reusable first stags. Only in the most pessimistic launch scenarios do the ELV achieve similar total cost than their counterparts with reusable first stages, but in no case are their total costs actually lower. For example, in the scenario leading to the lowest launch costs, the DRL CC GG Med has a non-recurring cost of 13 B€ and an average launch cost of 186 €, the equivalent ELV EL CC GG Med has a development costs of 8 B€ and an average launch cost of 314 M€. In this case the breakeven point is at ~ 40 launches. As the scenario requires 51 launches in both cases, the DRL configuration ends up (slightly) ahead even in this extreme case.

It seems that the breakeven point is below the most pessimistic cases captured via the market uncertainties, so at less than 2.6 launches per year (over 20 years).

5.6 Comparison of different propellants

The full results shown in Sect. 4.1 contain four different fuel options; however, for the purpose of this discussion, the focus will lie on hydrogen and methane as the current discussion of the future heavy-lift European launcher is focused on these options. The results of methane and the other hydrocarbons are similar enough that the discussion remains applicable to the other cases.

All hydrogen-fueled launchers are less costly than their methane-fueled counterparts, which is noteworthy given that hydrogen engines have approximately 30% higher recurring costs per unit of thrust. The difference is particularly significant for versions with VTVL first stages and gas generator engines, where methane-fueled variants are about 18% more expensive than their hydrogen equivalents. The smaller thrust-specific cost of methane-fueled systems is outweighed by the significantly larger propellant load, which results in substantially increased dry mass and thrust requirements. For instance, the DRL CC GG Med configuration requires nearly 2.5 times the thrust of its hydrogen-fueled counterpart, DRL HH GG Med.

When staged combustion engines are used, the cost difference between hydrogen- and methane-fueled DRL configurations narrows but remains significant at 13%. Methane-fueled configurations, with their initially lower specific impulse, benefit more from the increase in specific impulse than hydrogen-fueled configurations.

In cases with an IAC first stage, the cost difference between the two fuel options is smaller, around 10%, as expected, since this return method demands less Δv. Although the ENTRAIN study did not evaluate any methane-fueled VTHL versions with staged combustion engines, the trends observed suggest that such a combination could be promising.

Continuing from the singe-fuel launchers, the hybrid launchers, with a hydrogen-fueled upper stage and methane-fueled lower stage, remain competitive, even with the added cost of developing and producing two different engines. This results in 23% higher non-recurring costs, but only a minimal increase in recurring cost (0.3%), compared to the fully hydrogen-fueled version.

5.7 Comparison of different staging velocities

The sensitivity to staging varies significantly depending on the propellant choice and return method. This aligns with expectations from the rocket equation, as specific impulse and the total Δv budget largely determine the required total mass. As anticipated, the sensitivity is highest for hydrocarbon-fueled concepts with a VTVL first stage and lowest for hydrogen-fueled stages utilizing IAC and closed-cycle engines. Flyback configurations exhibit greater sensitivity to staging than IAC cases. Although the return flight in flyback configurations is powered by air-breathing engines and not directly linked to the main rocket propulsion, it still consumes fuel and, therefore, contributes to the overall Δv budget. As a result, higher staging velocities lead to increased stage sizes and, consequently, higher costs. This effect remains significant, even though this return method was only assessed for hydrogen-fueled configurations with closed-cycle engines, which, as mentioned earlier, are relatively insensitive to staging.

The IAC return method is better suited for higher separation velocities, while the development cost does also increase, the recurring cost falls sufficiently to compensate for this. In total cost, the medium and high separation velocity cases are almost identical.

For the configurations with vertically landing first stages, only the medium and high separation velocities were investigated within the ENTRAIN study. The low separation velocity lead to excessively large launchers for the hydrocarbon-fueled launchers due to the large Δv required of the upper stage in these cases, as described in Ref. [3]. For these cases, the medium staging velocity results in the lowest costs. While the high separation velocity theoretically results in a larger reusable fraction, this benefit is more than equalized by the increase in first stage size driven by the additional Δv required for acceleration and deceleration.

6 Conclusion

Within this paper, a cost estimation of the launchers from the ENTRAIN study is presented. Designed for a 7.5 t payload into GTO, different propellant combinations, engine cycles and recovery methods of a reusable first stage were investigated and the cost for various combinations analyzed.

In addition to the partially reusable launchers, a number of expendable two-staged launchers where evaluated in order to quantify the advantage possible through a reusable first stage.

In general, the results herein show that even the cost of launchers cannot escape the tyranny of the rocket equation. Even though adaptions were made to account for differences between the different design options (i.e., the assumptions of lower thrust-specific production cost for hydrocarbon-fueled engines, or higher thrust-specific cost of staged combustion engines), the results largely follow the trends established in the analysis of the dry mass in the previous technical discussions. Due to the high-performance requirements resulting from serving a GTO mission with a two-staged vehicle including reuse of the first stage, any change in specific impulse has a large impact on the system size. Therefore, even though on a subsystem level, a specific design option might appear desirable and cost-beneficial, the resulting increase in total launcher size might negate the specific cost savings entirely.

The main takeaways are listed below, in order of the magnitude of the difference found:

- Across all 5,000 launch market scenario samples considered in this study, launchers with reusable first stages enable significant cost savings compared to fully expendable versions.
- The use of hydrogen as a fuel results in significantly lower costs than fully hydrocarbon-fueled vehicles. The additional propellant and dry mass needed due to the lower specific impulse more than negate any potential cost benefits by lower production effort for hydrocarbon-fueled engines.
- The performance benefit of closed-cycle engines allows a reduction in overall stage size that results in lower total cost compared to the gas generator fueled version, even when considering increased thrust-specific development and production costs.
- Due to the nature of the parametric variation of the staging velocity, no exact staging optimum is identified. However, the medium separation velocity (ca. Mach 9) appears well suited. As expected, the sensitivity to the staging is higher the lower the specific impulse.
- With sufficiently low refurbishment costs and a high number of reuses, IAC first stages can amortize their additional development costs and become cheaper than the equivalent DRL stages. However, even in these cases, the differences are small, as the expendable fraction of the launch vehicles becomes the primary cost driver in both scenarios, making small differences in the costs of the reusable portions less impactful on the total cost. The comparison is clearer in the hydrocarbon-fueled cases, where IAC configurations show a greater advantage. This advantage arises from the reduced Δv budget of these missions using in-air-capturing technology compared to vertical landing, which particularly benefits lower specific impulse fuel options.

Appendix

See Tables 3, 4 and 5.

Table 3 Key parameters of investigated ELV launchers

Fuel	–	LH2	LCH4	Hybrid		
Engine cycle	–	GG	SC	GG	SC	GG
2nd-stage Δv	[km/s]	7.0	7.0	7.0	7.0	7.0
Staging category	–	Med	Med	Med	Med	Med
Designation	–	EL HH GG Med	EL HH SC Med	EL CC GG Med	EL CC SC Med	EL CH GG Med
1st stage						
Propellant loading	[t]	230	183	575	435	295
Total dry mass	[t]	26.0	22.7	43.9	37.4	22.0
Propulsion mass	[t]	6.4	6.7	13.1	13.9	6.8
No. of engines	[–]	7	7	11	9	7
Single engine thrust (sea level)	[kN]	711	572	992	949	802
2nd stage						
Propellant loading	[t]	75	64	148	125	70
Dry mass	[t]	6.7	5.7	7.8	7.1	6.1
Fairing	[t]	1.4	1.4	1.4	1.6	1.4
Propulsion mass	[t]	1.2	1.1	1.7	1.8	1.1
Engine thrust (vacuum)	[kN]	856	666	1198	1124	778
Total launcher						
Height	[m]	74.1	66.2	79.0	67.6	60.5
Diameter	[m]	5	5	5	5	5
Payload to GTO	[t]	7.57	7.55	7.41	7.54	7.51
GTO GLOM	[t]	355	291	799	627	411
Payload to SSO	[t]	15.0	13.8	18.5	17.5	14.6
SSO GLOM	[t]	362	297	810	637	419

Table 4 SSO Performance of selected ENTRAIN RLV launchers

Fuel	–	LH2	LCH4	Hybrid					
Engine cycle	–	GG	SC	GG	SC	GG	SC	GG	GG
2nd-stage Δv	[km/s]	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Staging category	–	Med	Med	Med	Med	Med	Med	Med	Med
Designation	–	VL HH GG Med	VL HH SC Med	HL HH GG Med	HL HH SC Med	VL CC GG Med	VL CC SC Med	HL CC GG Med	VL CH GG Med
SSO performance									
Payload to SSO with RTLS	[t]	10.3	9.8	–	–	9.6	10.4	–	9.7
Payload to SSO	[t]	14.9	13.5	14.3	14.1	18.1	16.9	17.9	14.4
SSO GLOM	[t]	455	374	391	335	1119	845	826	577

Table 5 Coefficients and CER data used for parametric cost estimations

Launcher	Element	*a*_dev	*x*_dev	*a*_prod	*x*_prod	f_1	f_2	f_3	f_5	*p*	*p*_refurb	Reuses
FB_HH_SC_HI	First stage	331	0.377	1.84	0.59	1	1	1	0.023	0.85	0.85	50
	Reentry HW	0.899	0.972	1.901	0.59	1	1	1	0.023	0.85	0.85	50
	Landing HW	1.121	0.916	0.839	0.59	1	1	1	0.023	0.85	0.85	50
	GNC	2000	1	0	1	1	1	1	–	1	–	–
	A/B propulsion	0.432	1	0.029	1	1.1	0.73	1	0	1	0.85	50
	SL engine	277	0.48	1.2	0.535	1.1	0.73	1	0.04	0.85	0.85	25
	Interstage	0.079	1	0.005	1	0.7	1	1	–	0.85	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Vac. engine	277	0.48	1.2	0.535	1.1	0.73	1	–	0.85	–	–
FB_HH_SC_MED	First stage	331	0.377	1.84	0.59	1	1	1	0.023	0.85	0.85	50
	Reentry HW	0.899	0.972	1.901	0.59	1	1	1	0.023	0.85	0.85	50
	Landing HW	1.121	0.916	0.839	0.59	1	1	1	0.023	0.85	0.85	50
	GNC	2000	1	0	1	1	1	1	–	1	–	–
	A/B propulsion	0.432	1	0.029	1	1.1	0.73	1	0	1	0.85	50
	SL engine	277	0.48	1.2	0.535	1.1	0.73	1	0.04	0.85	0.85	25
	Interstage	0.079	1	0.005	1	0.7	1	1	–	0.85	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Vac. engine	277	0.48	1.2	0.535	1.1	0.73	1	–	0.85	–	–
FB_HH_SC_LOW	First stage	331	0.377	1.84	0.59	1	1	1	0.023	0.85	0.85	50
	Reentry HW	0.899	0.972	1.901	0.59	1	1	1	0.023	0.85	0.85	50
	Landing HW	1.121	0.916	0.839	0.59	1	1	1	0.023	0.85	0.85	50
	GNC	2000	1	0	1	1	1	1	–	1	–	–
	A/B propulsion	0.432	1	0.029	1	1.1	0.73	1	0	1	0.85	50
	SL engine	277	0.48	1.2	0.535	1.1	0.73	1	0.04	0.85	0.85	25
	Interstage	0.079	1	0.005	1	0.7	1	1	–	0.85	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Vac. engine	277	0.48	1.2	0.535	1.1	0.73	1	–	0.85	–	–
HL_HH_SC_HI	First stage	331	0.377	1.84	0.59	1	1	1	0.023	0.85	0.85	50
	Reentry HW	0.899	0.972	1.901	0.59	1	1	1	0.023	0.85	0.85	50
	Landing HW	1.121	0.916	0.839	0.59	1	1	1	0.023	0.85	0.85	50
	GNC	2200	1	0	1	1	1	1	–	1	–	–
	SL engine	277	0.48	1.2	0.535	1.1	0.73	1	0.04	0.85	0.85	25
	Interstage	0.079	1	0.005	1	0.7	1	1	–	0.85	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Vac. engine	277	0.48	1.2	0.535	1.1	0.73	1	–	0.85	–	–
HL_HH_SC_MED	First stage	331	0.377	1.84	0.59	1	1	1	0.023	0.85	0.85	50
	Reentry HW	0.899	0.972	1.901	0.59	1	1	1	0.023	0.85	0.85	50
	Landing HW	1.121	0.916	0.839	0.59	1	1	1	0.023	0.85	0.85	50
	GNC	2200	1	0	1	1	1	1	–	1	–	–
	SL engine	277	0.48	1.2	0.535	1.1	0.73	1	0.04	0.85	0.85	25
	Interstage	0.079	1	0.005	1	0.7	1	1	–	0.85	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Vac. engine	277	0.48	1.2	0.535	1.1	0.73	1	–	0.85	–	–
HL_HH_SC_LOW	First stage	331	0.377	1.84	0.59	1	1	1	0.023	0.85	0.85	50
	Reentry HW	0.899	0.972	1.901	0.59	1	1	1	0.023	0.85	0.85	50
	Landing HW	1.121	0.916	0.839	0.59	1	1	1	0.023	0.85	0.85	50
	GNC	2200	1	0	1	1	1	1	–	1	–	–
	SL engine	277	0.48	1.2	0.535	1.1	0.73	1	0.04	0.85	0.85	25
	Interstage	0.079	1	0.005	1	0.7	1	1	–	0.85	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–

Table 5 (continued)

Launcher	Element	*a*_dev	*x*_dev	*a*_prod	*x*_prod	f_1	f_2	f_3	f_5	*p*	*p*_refurb	Reuses
	Vac. engine	277	0.48	1.2	0.535	1.1	0.73	1	–	0.85	–	–
HL_HH_GG_MED	First stage	331	0.377	1.84	0.59	1	1	1	0.023	0.85	0.85	50
	Reentry HW	0.899	0.972	1.901	0.59	1	1	1	0.023	0.85	0.85	50
	Landing HW	1.121	0.916	0.839	0.59	1	1	1	0.023	0.85	0.85	50
	GNC	2200	1	0	1	1	1	1	–	1	–	–
	SL engine	277	0.48	1.2	0.535	1	0.73	1	0.04	0.85	0.85	25
	Interstage	0.079	1	0.005	1	0.7	1	1	–	0.85	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Vac. engine	277	0.48	1.2	0.535	1	0.73	1	–	0.85	–	–
HL_CC_GG_MED	First stage	331	0.377	1.84	0.59	1	1	1	0.023	0.85	0.85	50
	Reentry HW	0.899	0.972	1.369	0.59	1	1	1	0.023	0.85	0.85	50
	Landing HW	1.121	0.916	0.839	0.59	1	1	1	0.023	0.85	0.85	50
	GNC	2200	1	0	1	1	1	1	–	1	–	–
	SL engine	277	0.48	1.2	0.535	1.1	0.73	1	0.04	0.85	0.85	25
	Interstage	0.079	1	0.005	1	0.7	1	1	–	0.85	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Vac. engine	277	0.48	1.2	0.535	1.1	0.73	1	–	0.85	–	–
HL_KK_GG_MED	First stage	331	0.377	1.84	0.59	1	1	1	0.023	0.85	0.85	50
	Reentry HW	0.899	0.972	1.369	0.59	1	1	1	0.023	0.85	0.85	50
	Landing HW	1.121	0.916	0.839	0.59	1	1	1	0.023	0.85	0.85	50
	GNC	2200	1	0	1	1	1	1	–	1	–	–
	SL engine	277	0.48	1.2	0.535	1.1	0.73	1	0.04	0.85	0.85	25
	Interstage	0.079	1	0.005	1	0.7	1	1	–	0.85	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Vac. engine	277	0.48	1.2	0.535	1.1	0.73	1	–	0.85	–	–
VL_HH_GG_HI	First stage	331	0.377	1.84	0.59	1	1	1	0.06	0.85	0.85	25
	Interstage	0.079	1	0.005	1	1	1	1	0.06	0.85	0.85	25
	Reentry HW	0.899	0.972	1.901	0.59	1	1	1	0.06	0.85	0.85	25
	Landing HW	1.121	0.916	0.839	0.59	1	1	1	0.06	0.85	0.85	25
	SL engine	277	0.48	1.2	0.535	1	0.85	1	0.07	0.85	0.85	20
	GNC	2500	1	0	1	1	1	1	–	1	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Vac. engine	277	0.48	1.2	0.535	1	0.85	1	–	0.85	–	–
VL_HH_GG_MED	First stage	331	0.377	1.84	0.59	1	1	1	0.06	0.85	0.85	25
	Interstage	0.079	1	0.005	1	1	1	1	0.06	0.85	0.85	25
	Reentry HW	0.899	0.972	1.901	0.59	1	1	1	0.06	0.85	0.85	25
	Landing HW	1.121	0.916	0.839	0.59	1	1	1	0.06	0.85	0.85	25
	SL engine	277	0.48	1.2	0.535	1	0.85	1	0.07	0.85	0.85	20
	GNC	2500	1	0	1	1	1	1	–	1	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Vac. engine	277	0.48	1.2	0.535	1	0.85	1	–	0.85	–	–
VL_CH_GG_MED	First stage	331	0.377	1.84	0.59	1	1	1	0.06	0.85	0.85	25
	Interstage	0.079	1	0.003	1	1	1	1	0.06	0.85	0.85	25
	Reentry HW	0.899	0.972	1.901	0.59	1	1	1	0.06	0.85	0.85	25
	Landing HW	1.121	0.916	0.839	0.59	1	1	1	0.06	0.85	0.85	25
	SL engine	277	0.48	1.2	0.535	1.1	0.85	1	0.07	0.85	0.85	20
	GNC	2500	1	0	1	1	1	1	–	1	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Vac. engine	277	0.48	1.2	0.535	1	0.85	1	–	0.85	–	–
VL_HH_SC_MED	First stage	331	0.377	1.84	0.59	1	1	1	0.06	0.85	0.85	25

Table 5 (continued)

Launcher	Element	*a*_dev	*x*_dev	*a*_prod	*x*_prod	f_1	f_2	f_3	f_5	*p*	*p*_refurb	Reuses
	Interstage	0.079	1	0.005	1	1	1	1	0.06	0.85	0.85	25
	Reentry HW	0.899	0.972	1.901	0.59	1	1	1	0.06	0.85	0.85	25
	Landing HW	1.121	0.916	0.839	0.59	1	1	1	0.06	0.85	0.85	25
	SL engine	277	0.48	1.2	0.535	1.1	0.85	1	0.07	0.85	0.85	20
	GNC	2500	1	0	1	1	1	1	–	1	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Vac. engine	277	0.48	1.2	0.535	1.1	0.85	1	–	0.85	–	–
VL_CC_GG_HI	First stage	331	0.377	1.84	0.59	1	1	1	0.06	0.85	0.85	25
	Interstage	0.079	1	0.003	1	1	1	1	0.06	0.85	0.85	25
	Reentry HW	0.899	0.972	1.901	0.59	1	1	1	0.06	0.85	0.85	25
	Landing HW	1.121	0.916	0.604	0.59	1	1	1	0.06	0.85	0.85	25
	SL engine	277	0.48	1.2	0.535	1.1	0.85	1	0.07	0.85	0.85	20
	GNC	2500	1	0	1	1	1	1	–	1	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Vac. engine	277	0.48	1.2	0.535	1.1	0.85	1	–	0.85	–	–
VL_CC_GG_MED	First stage	331	0.377	1.84	0.59	1	1	1	0.06	0.85	0.85	25
	Interstage	0.079	1	0.003	1	1	1	1	0.06	0.85	0.85	25
	Reentry HW	0.899	0.972	1.901	0.59	1	1	1	0.06	0.85	0.85	25
	Landing HW	1.121	0.916	0.604	0.59	1	1	1	0.06	0.85	0.85	25
	SL engine	277	0.48	1.2	0.535	1.1	0.85	1	0.07	0.85	0.85	20
	GNC	2500	1	0	1	1	1	1	–	1	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Vac. engine	277	0.48	1.2	0.535	1.1	0.85	1	–	0.85	–	–
VL_CC_SC_MED	First stage	331	0.377	1.84	0.59	1	1	1	0.06	0.85	0.85	25
	Interstage	0.079	1	0.003	1	1	1	1	0.06	0.85	0.85	25
	Reentry HW	0.899	0.972	1.901	0.59	1	1	1	0.06	0.85	0.85	25
	Landing HW	1.121	0.916	0.604	0.59	1	1	1	0.06	0.85	0.85	25
	SL engine	277	0.48	1.2	0.535	1.21	0.85	1	0.07	0.85	0.85	20
	GNC	2500	1	0	1	1	1	1	–	1	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Vac. engine	277	0.48	1.2	0.535	1.21	0.85	1	–	0.85	–	–
VL_KK_GG_HI	First stage	331	0.377	1.84	0.59	1	1	1	0.06	0.85	0.85	25
	Interstage	0.079	1	0.003	1	1	1	1	0.06	0.85	0.85	25
	Reentry HW	0.899	0.972	1.901	0.59	1	1	1	0.06	0.85	0.85	25
	Landing HW	1.121	0.916	0.604	0.59	1	1	1	0.06	0.85	0.85	25
	SL engine	277	0.48	1.2	0.535	1.1	0.85	1	0.07	0.85	0.85	20
	GNC	2500	1	0	1	1	1	1	–	1	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Vac. engine	277	0.48	1.2	0.535	1.1	0.85	1	–	0.85	–	–
VL_KK_GG_MED	First stage	331	0.377	1.84	0.59	1	1	1	0.06	0.85	0.85	25
	Interstage	0.079	1	0.003	1	1	1	1	0.06	0.85	0.85	25
	Reentry HW	0.899	0.972	1.901	0.59	1	1	1	0.06	0.85	0.85	25
	Landing HW	1.121	0.916	0.604	0.59	1	1	1	0.06	0.85	0.85	25
	SL engine	277	0.48	1.2	0.535	1.1	0.85	1	0.07	0.85	0.85	20
	GNC	2500	1	0	1	1	1	1	–	1	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Vac. engine	277	0.48	1.2	0.535	1.1	0.85	1	–	0.85	–	–
VL_PP_GG_HI	First stage	331	0.377	1.84	0.59	1	1	1	0.06	0.85	0.85	25
	Interstage	0.079	1	0.003	1	1	1	1	0.06	0.85	0.85	25
	Reentry HW	0.899	0.972	1.901	0.59	1	1	1	0.06	0.85	0.85	25

Table 5 (continued)

Launcher	Element	*a*_dev	*x*_dev	*a*_prod	*x*_prod	f_1	f_2	f_3	f_5	*p*	*p*_refurb	Reuses
	Landing HW	1.121	0.916	0.604	0.59	1	1	1	0.06	0.85	0.85	25
	SL engine	277	0.48	1.2	0.535	1.1	0.85	1	0.07	0.85	0.85	20
	GNC	2500	1	0	1	1	1	1	–	1	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Vac. engine	277	0.48	1.2	0.535	1.1	0.85	1	–	0.85	–	–
EL_HH_SC_MiED	First stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Interstage	0.079	1	0.005	1	0.7	1	1	–	0.85	–	–
	SL engine	277	0.48	1.667	0.535	1.1	0.65	1	–	0.85	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Vac. engine	277	0.48	1.667	0.535	1.1	0.65	1	–	0.85	–	–
EL_HH_GG_MED	First stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Interstage	0.079	1	0.005	1	0.7	1	1	–	0.85	–	–
	SL engine	277	0.48	1.667	0.535	1	0.65	1	–	0.85	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Vac. engine	277	0.48	1.667	0.535	1	0.65	1	–	0.85	–	–
EL_CH_GG_MED	First stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Interstage	0.079	1	0.005	1	0.7	1	1	–	0.85	–	–
	SL engine	277	0.48	1.2	0.535	1.1	0.65	1	–	0.85	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Vac. engine	277	0.48	1.667	0.535	1	0.65	1	–	0.85	–	–
EL_CC_GG_MED	First stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Interstage	0.079	1	0.005	1	0.7	1	1	–	0.85	–	–
	SL engine	277	0.48	1.2	0.535	1.1	0.65	1	–	0.85	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Vac. engine	277	0.48	1.2	0.535	1.1	0.65	1	–	0.85	–	–
EL_CC_SC_MED	First stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Interstage	0.079	1	0.005	1	0.7	1	1	–	0.85	–	–
	SL engine	277	0.48	1.2	0.535	1.21	0.65	1	–	0.85	–	–
	Second stage	331	0.377	1.84	0.59	0.7	1	1	–	0.85	–	–
	Vac. engine	277	0.48	1.2	0.535	1.21	0.65	1	–	0.85	–	–

Author contributions J.W. performed the cost analysis and wrote the majority of the manuscript. M.H. conducted the technical analysis related to the ELV launcher design and the SSO payload assessment for the ENTRAIN launchers, and authored the corresponding sections of the manuscript. M.S. contributed with conceptualization, supervision, and review of the manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors have no relevant financial or nonfinancial interests to disclose.

Content to publish During the preparation of this work, the authors used ChatGPT 4o in order to revise the text. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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