

Article

Sustainability Assessment of Liquid Hydrogen Aircraft Tanks

Aikaterini Anagnostopoulou ¹, Dimitris G. Sotiropoulos ², Konstantinos Tserpes ^{1,*}, George Tzoumakis ¹, George Lampeas ¹ and Konstantinos Fotopoulos ¹

¹ Laboratory of Technology & Strength of Materials, Department of Mechanical Engineering & Aeronautics, University of Patras, 26500 Patras, Greece; aikat.anagnostopoulou@ac.upatras.gr (A.A.); gtzoumakis@upnet.gr (G.T.); lampeas@upatras.gr (G.L.); kostasfot@upatras.gr (K.F.)

² Department of Electrical and Computer Engineering, University of Peloponnese, 26334 Patras, Greece; dg.sotiropoulos@uop.gr

* Correspondence: kitserpes@upatras.gr

Abstract

Using liquid hydrogen (LH₂) in aviation creates a difficult design problem for cryogenic storage systems, especially in the early design stage. At that point, environmental, economic, and technical aspects need to be considered together. Here, a sustainability assessment framework is presented for LH₂ aircraft storage tank configurations from a life-cycle perspective. The study includes 24 design alternatives. These are obtained by changing the material combinations of the main structural components, while the overall tank architecture is kept unchanged. The environmental and economic dimensions are assessed through life-cycle assessment (LCA) and life-cycle costing (LCC), whereas the technical dimension is represented by the system mass. Since the relative importance of the criteria is usually not fixed at this stage, Unweighted TOPSIS (UW-TOPSIS) is first used to examine the alternatives under different weighting scenarios. The most competitive solutions are then re-evaluated by a standardised TOPSIS variant (vector-normalised weights, Z-standardised distances) with objective weighting methods. The results show that the configurations based entirely on Al2219-T8 for the main structural components remain top-ranked and more stable under the examined scenarios, whereas mixed-material configurations are more sensitive to changes in weighting assumptions. In this way, the exploratory stage is kept separate from the later weighting stage, where the weights are computed from the decision matrix of the reduced set. This is suitable for early aerospace design, where subjective preferences are often not yet available.

Keywords: sustainability assessment; hydrogen aviation; liquid hydrogen storage tanks; Unweighted TOPSIS; interval weights; life-cycle assessment; life-cycle costing



Academic Editors: Jamil Toyir and Yinlun Huang

Received: 13 May 2026

Revised: 9 June 2026

Accepted: 24 June 2026

Published: 26 June 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Aviation must reduce its environmental burden if the broader climate targets of the Paris Agreement are to be met [1]. This requirement has renewed interest in zero-emission aircraft concepts. Among the available options, liquid hydrogen (LH₂) is often discussed as a promising energy carrier because it does not emit carbon at the point of use and may support long-range flight. Still, the assessment of LH₂-based aviation cannot stop at in-flight operation. Its overall performance depends on the whole chain, including hydrogen production, liquefaction, distribution, and the aircraft technologies needed to store and use it, especially cryogenic tanks and propulsion systems. Recent studies suggest that, even though LH₂ may require more energy during flight, it can perform better than

sustainable aviation fuels (SAFs) when the comparison is made on a life-cycle basis [2]. This makes a system-level and life-cycle-based assessment necessary [3]. A similar perspective also appears in current European research programmes, including H2ELIOS, where fuel pathways and aircraft technologies are examined together in the broader effort toward climate-neutral aviation.

The literature on alternative aviation fuels points in the same direction. Several studies show that environmental gains cannot be judged only from in-flight emissions, because upstream production stages and supply-chain effects also contribute [4,5]. Even so, much of this work still focuses mainly on environmental performance. Economic and technical aspects, although also important in engineering design, are often treated more briefly or left outside the analysis. Some more recent studies have started to link environmental assessment with aircraft design and, in some cases, with economic considerations as well [6]. These studies make clear that a shift to fuels such as LH₂ would also affect aircraft layout and system design.

For LH₂ cryogenic tanks, material selection and structural design are especially important. The main trade-off is usually between metallic and composite solutions [7]. Carbon fibre-reinforced polymers (CFRPs), for example, are attractive because of their high strength-to-weight ratio and their potential to reduce mass [8]. At the same time, their production and end-of-life treatment may create environmental and economic burdens [9]. Their use in LH₂ tank applications is also limited by practical concerns, including long-term durability, microcracking, permeability, and inspectability [7].

Related life-cycle studies, many of them from the automotive field, show that hydrogen storage systems may contribute substantially to total environmental impacts and may involve nontrivial trade-offs in both energy use and cost [9,10]. Taken together, these results suggest two things. First, environmental and economic dimensions are still often analysed separately. Second, LH₂ aviation systems need evaluation frameworks that can address several dimensions at the same time. In practice, LH₂ storage is a multi-criteria problem, since environmental, economic, and technical criteria have to be considered together and may point in different directions. Similar situations also arise in other energy systems, where trade-offs have to be examined over the full life cycle [11].

For problems of this kind, multi-criteria decision-making (MCDM) methods are a natural option. They have already been applied in aerospace design, including the authors' earlier studies on aircraft structures, where environmental, economic, and technical criteria were analysed jointly and the effects of material choice, geometry, and joining strategy were examined in a systematic way [12,13]. In those studies, objective weighting methods were used so that criterion importance came from the data rather than from subjective judgement. Even so, the issue of weighting is still difficult, especially at an early design stage. At that point, stakeholder preferences are often not fixed, while the ranking of alternatives may still depend strongly on the chosen weights. Methods such as Unweighted TOPSIS (UW-TOPSIS) were proposed for this reason. They allow the analyst to work with weight intervals instead of fixed weights and therefore avoid prescribing criterion importance in advance [14,15].

In the specific case of LH₂ storage systems, there are still few sustainability assessment studies that use MCDM while also treating uncertainty in criterion importance explicitly. The present study addresses that gap. It develops a decision framework for LH₂ storage configurations and uses it to compare alternative designs while also examining how sensitive the ranking is to the weighting scheme. UW-TOPSIS is used first, in order to explore the design space without fixed weights. The alternatives that remain competitive across the explored weighting conditions are selected for further analysis, and a standardised TOPSIS variant with data-driven weighting methods is then applied in the second stage to

this reduced set of alternatives. In this way, the first stage reveals how much the ranking depends on the choice of weights, whereas the second stage derives the final weights directly from the reduced decision matrix. As a result, subjective weighting assumptions do not determine the final choice among the LH₂ storage configurations studied here.

2. Technological Problem

This section examines the sustainability performance of liquid hydrogen (LH₂) storage tank configurations for zero-emission aircraft. The analysis starts from a baseline design developed in the H2ELIOS project. The goal is to identify the configurations that perform best when environmental, economic, and technical criteria are considered together under different design priorities. The main difficulty at this stage is that the relative importance of these criteria is usually not agreed in advance. For that reason, the first part of the analysis applies Unweighted TOPSIS (UW-TOPSIS), so that the alternatives can be explored under admissible weight intervals. The alternatives that remain competitive are then re-examined by a standardised TOPSIS variant with objective weighting methods. This gives a more focused comparison of the candidate configurations.

Tank Configuration and Design Space

The LH₂ tank considered in this study, shown in Figure 1, has a fixed geometry and a fixed system layout. The different colors distinguish the main tank subcomponents, namely the outer tank, inner tank, outer supports, inner supports, and the remaining visible auxiliary components. This reflects both the complexity of cryogenic tank design and the strict functional requirements that such systems must satisfy. Geometric variations are therefore outside the scope of the present analysis. The candidate materials considered for the main subcomponents of the baseline tank design were taken from the preliminary designs developed within the H2ELIOS project. Based on these candidate materials, the design space is defined by the material selection for four main structural parts, the outer tank, the inner tank, the outer supports, and the inner supports, while the remaining tank architecture, including the insulation system and auxiliary components, remains unchanged across all investigated alternatives.

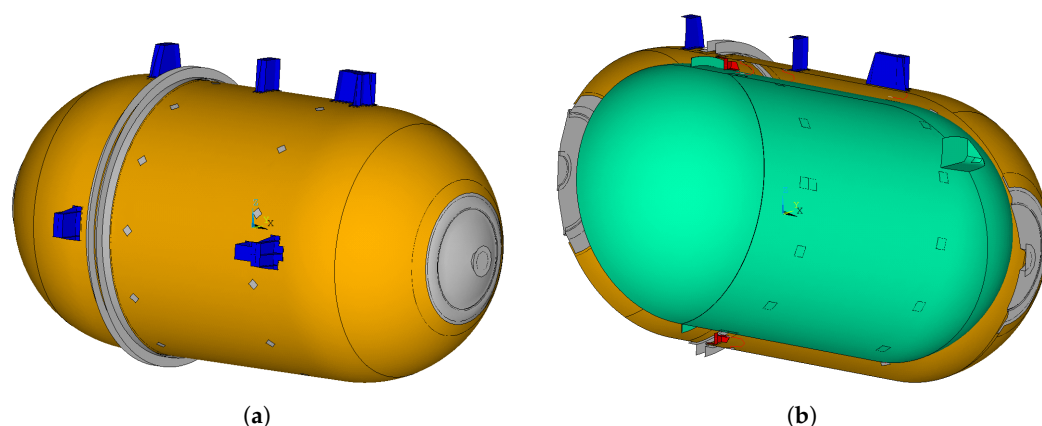


Figure 1. (a) Outer tank configuration of the LH₂ storage system, illustrating the complete external geometry of the assembly. (b) Sectional view showing the internal configuration.

Under these assumptions, the feasible alternatives come from the different material combinations selected for the main structural components. This gives 24 configurations in total. Together, they cover all combinations of the available material options for the inner tank, outer tank, and support structures. These configurations constitute the set of decision alternatives considered in this study. Their main characteristics are listed in Table 1.

Table 1. Characteristics of the LH₂ storage tank design alternatives.

ID	Outer Tank	Inner Tank	Outer Supports	Inner Supports
S01	Al2219-T8	Al2219-T8	Al2219-T8	Al2219-T8
S02	Al2219-T8	Al2219-T8	Al2219-T8	AISI 316L
S03	Al2219-T8	Al2219-T8	AISI 316L	Al2219-T8
S04	Al2219-T8	Al2219-T8	AISI 316L	AISI 316L
S05	Al2219-T8	AISI 316L	Al2219-T8	Al2219-T8
S06	Al2219-T8	AISI 316L	Al2219-T8	AISI 316L
S07	Al2219-T8	AISI 316L	AISI 316L	Al2219-T8
S08	Al2219-T8	AISI 316L	AISI 316L	AISI 316L
S09	Al2219-T8	CFRP	Al2219-T8	Al2219-T8
S10	Al2219-T8	CFRP	Al2219-T8	AISI 316L
S11	Al2219-T8	CFRP	AISI 316L	Al2219-T8
S12	Al2219-T8	CFRP	AISI 316L	AISI 316L
S13	AISI 316L	Al2219-T8	Al2219-T8	Al2219-T8
S14	AISI 316L	Al2219-T8	Al2219-T8	AISI 316L
S15	AISI 316L	Al2219-T8	AISI 316L	Al2219-T8
S16	AISI 316L	Al2219-T8	AISI 316L	AISI 316L
S17	AISI 316L	AISI 316L	Al2219-T8	Al2219-T8
S18	AISI 316L	AISI 316L	Al2219-T8	AISI 316L
S19	AISI 316L	AISI 316L	AISI 316L	Al2219-T8
S20	AISI 316L	AISI 316L	AISI 316L	AISI 316L
S21	AISI 316L	CFRP	Al2219-T8	Al2219-T8
S22	AISI 316L	CFRP	Al2219-T8	AISI 316L
S23	AISI 316L	CFRP	AISI 316L	Al2219-T8
S24	AISI 316L	CFRP	AISI 316L	AISI 316L

The candidate materials used for the varying structural components are aluminium alloy Al2219-T8, stainless steel AISI 316L, and carbon fibre-reinforced polymer (CFRP). The 24 alternatives are arranged into six groups according to the outer-tank and inner-tank material pair, as shown in Table 2, in order to support the comparative discussion of the resulting sustainability trends. Inside each group, the four cases differ only in the material assignment of the outer and inner supports, which can be either Al2219-T8 or AISI 316L. The insulation system and the auxiliary materials are included in the environmental, economic, and technical evaluation of every alternative. More detailed information on the material composition of the subcomponents is given in Appendix A (Tables A1–A4), while the mass distribution for the reference scenario is reported in Appendix B (Table A5).

Table 2. Material group classification of the LH₂ tank design alternatives.

Group	Outer Tank	Inner Tank	Alternatives
G1	Al2219-T8	Al2219-T8	S01–S04
G2	Al2219-T8	AISI 316L	S05–S08
G3	Al2219-T8	CFRP	S09–S12
G4	AISI 316L	Al2219-T8	S13–S16
G5	AISI 316L	AISI 316L	S17–S20
G6	AISI 316L	CFRP	S21–S24

3. Sustainability Assessment

The assessment procedure used in this study (Figure 2) follows the general line of the framework presented in [12], but it is adapted here to LH₂ tank configurations. The alternatives are evaluated with respect to three dimensions: environmental performance, from an LCA; economic performance, from an LCC; and technical performance, represented

by mass. In all cases, lower values are preferred, so every criterion is treated as a cost-type attribute.

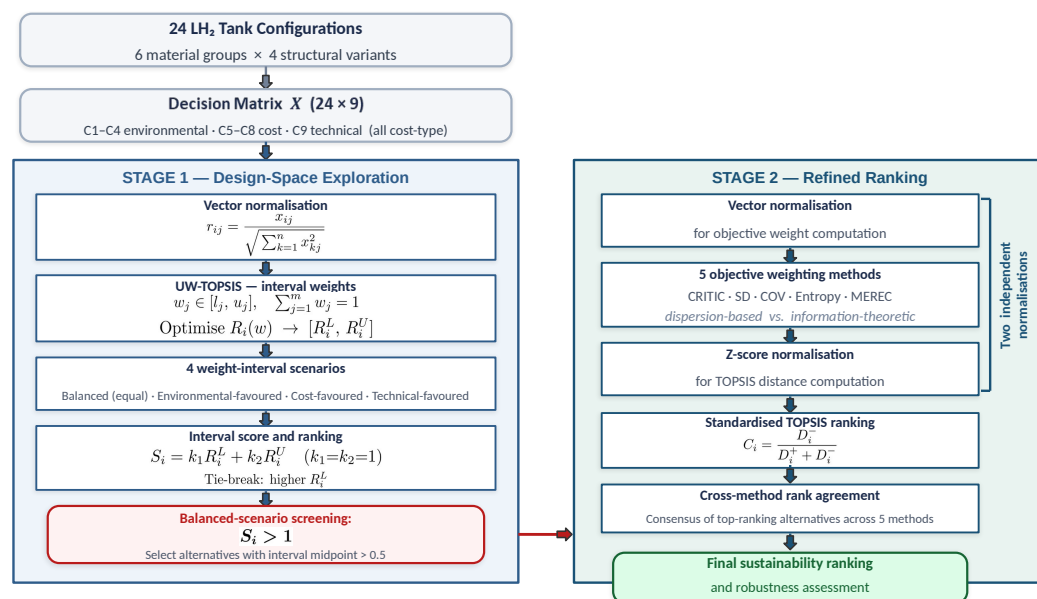


Figure 2. Two-stage sustainability assessment framework for LH₂ tank configurations. Stage 1 uses UW-TOPSIS for design-space exploration and screening, whereas stage 2 applies a standardised TOPSIS variant (vector-normalised weights, Z-standardised distances) with objective weighting methods to obtain the final sustainability ranking.

The design space contains 24 configurations, obtained from different material combinations for the main structural components. The analysis is carried out in two stages. First, UW-TOPSIS is used to examine the alternatives under several admissible weighting scenarios, since fixed criterion weights are not yet available at this stage of the design process. Then, after the most competitive configurations have been identified, a second analysis is performed with a standardised TOPSIS variant (vector-normalised weights combined with Z-standardised distances) together with objective weighting methods. In this way, the initial screening is separated from the later step in which criterion weights are fixed.

3.1. Construction of the Decision Matrix

The decision matrix is formed by placing the LH₂ tank alternatives in the rows and the sustainability criteria in the columns. Each entry gives the value of one alternative under one criterion. This arrangement allows the environmental, economic, and technical dimensions to be examined together.

3.1.1. Sustainability Criteria

The analysis uses four environmental criteria, four economic criteria, and one technical criterion. Together, they cover the sustainability dimensions considered in this study. The social dimension is not included. The criteria are listed in Table 3. Their values were obtained from LCA and LCC calculations carried out with SimaPro 10.2.0.0 and the Ecoinvent 3 database.

3.1.2. Environmental Criteria

The LCA follows ISO 14040 and ISO 14044 [16,17]. A cradle-to-grave boundary is adopted. It includes material production, manufacturing, use, and end-of-life processes. En-

Environmental impacts are calculated with the ReCiPe 2016 Endpoint method. The functional unit is one LH₂ aircraft tank.

Table 3. Criteria description and categorisation for the sustainability assessment of LH₂ tank configurations.

Criterion	Description	Category	Impact Type
C1	Human health (DALYs)	Environment	Minimise
C2	Ecosystems (species·yr)	Environment	Minimise
C3	Resources (USD 2013)	Environment	Minimise
C4	Global warming potential (kg CO ₂ eq.)	Environment	Minimise
C5	Material cost (EUR)	Cost	Minimise
C6	Energy cost (EUR)	Cost	Minimise
C7	Use cost (EUR)	Cost	Minimise
C8	End-of-life cost (EUR)	Cost	Minimise
C9	Mass (kg)	Technical	Minimise

The LCA and LCC models are based on the following assumptions:

- Al2219-T8 and steel components are assumed to be fully recycled at end of life; all remaining materials are assumed to go to landfill.
- Maintenance and transportation are excluded from the system boundaries.
- The use phase is modelled from the amount of hydrogen (kg H₂) needed to transport 1 kg of LH₂ tank mass over 1 km, using the Piaggio P. 180 Avanti as the reference aircraft. Hydrogen combustion itself does not produce CO₂, but the impacts from hydrogen production and liquefaction are included.
- The mass of each configuration is estimated from the specific strength of the corresponding material.

The LCA was implemented in SimaPro 10.2.0.0. The life-cycle inventory (LCI), including material composition and mass distribution, is based mainly on Ecoinvent 3 datasets, supplemented where needed by data from the literature.

3.1.3. Cost Criteria

The economic evaluation is carried out by a conventional LCC approach within the same SimaPro environment. The system boundary is the same as in the LCA, so that the environmental and economic assessments remain aligned. The cost model includes material cost, manufacturing cost, use-phase cost, and end-of-life cost. No revenues from recovered materials are assumed. End-of-life processes are treated only as costs.

3.1.4. Technical Criterion

The technical criterion is tank mass. This choice is motivated by the use phase, since lower mass leads to lower hydrogen demand for transportation. Other technical measures could be considered for a single design, but for a comparison across several alternatives with different material combinations it is difficult to define one common structural metric. For this reason, mass is used here as the technical indicator. The masses of the alternatives are estimated from equivalent-mass relations based on specific strength:

$$m_{Al} = \frac{m_{AlSi} \cdot \sigma_{sp,AlSi}}{\sigma_{sp,Al}} \quad (1)$$

$$m_{PC+CF} = \frac{m_{AlSi} \cdot \sigma_{sp,AlSi}}{\sigma_{sp,PC+CF}} \quad (2)$$

where σ_{sp} denotes specific ultimate strength. The corresponding material properties are given in Table 4. In the design-space tables, CFRP is used as a shorthand label for the composite inner-tank option. For the equivalent-mass calculation, this option is represented by PC + 20 wt% CF (polycarbonate with 20% carbon fibre by weight), whose specific strength is reported in Table 4.

Table 4. Mechanical properties and specific strength of alternative materials.

Material	Tensile Strength (MPa)	Density (g/cm ³)	Specific Strength (MPa·cm ³ /g)
AISI 316L	580	7.97	72.77
Al2219-T8	450	2.84	158.45
PC + 20% CF	57.92	1.30	44.55

3.2. Stage 1: Sustainability Assessment Using UW-TOPSIS

The sustainability performance of the LH₂ tank configurations is first evaluated with the Unweighted TOPSIS (UW-TOPSIS) method of Liern and Pérez-Gladish [14,15]. In contrast to classical TOPSIS, where each criterion weight is fixed in advance, UW-TOPSIS allows the weights to vary within a feasible region. This makes it possible to rank the alternatives even when the relative importance of the criteria has not yet been fixed.

Let $X = [x_{ij}]$ be the decision matrix, where $i = 1, \dots, n$ denotes the alternatives and $j = 1, \dots, m$ denotes the criteria. The vector-normalised matrix $R = [r_{ij}]$ is

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{k=1}^n x_{kj}^2}}, \quad i = 1, \dots, n, \quad j = 1, \dots, m. \quad (3)$$

Because all criteria are of the cost type, the positive and negative ideal values are

$$r_j^+ = \min_i r_{ij}, \quad r_j^- = \max_i r_{ij}, \quad j = 1, \dots, m. \quad (4)$$

The weight of criterion j is allowed to vary within an interval $[l_j, u_j]$. The feasible weight set is therefore

$$\Omega = \left\{ w \in \mathbb{R}^m : \sum_{j=1}^m w_j = 1, \quad l_j \leq w_j \leq u_j, \quad j = 1, \dots, m \right\}. \quad (5)$$

In stage 1, the criterion weights are applied to the normalised matrix before the Euclidean distances are computed, following the UW-TOPSIS formulation in [14,15]. For each admissible vector $w \in \Omega$, let $V(w)$ be the weighted normalised matrix with entries

$$v_{ij}(w) = w_j r_{ij}, \quad i = 1, \dots, n, \quad j = 1, \dots, m, \quad (6)$$

and define the weighted ideal coordinates by $v_j^+(w) = w_j r_j^+$ and $v_j^-(w) = w_j r_j^-$. The Euclidean distances of alternative A_i from the positive and negative ideal points in this weighted space are then

$$D_i^+(w) = \left[\sum_{j=1}^m (v_{ij}(w) - v_j^+(w))^2 \right]^{1/2}, \quad D_i^-(w) = \left[\sum_{j=1}^m (v_{ij}(w) - v_j^-(w))^2 \right]^{1/2}. \quad (7)$$

Substituting $v_{ij}(w) = w_j r_{ij}$ and $v_j^\pm(w) = w_j r_j^\pm$ gives the equivalent form

$$D_i^\pm(w) = \left[\sum_{j=1}^m w_j^2 (r_{ij} - r_j^\pm)^2 \right]^{1/2}, \quad (8)$$

so the weights operate inside the weighted TOPSIS space rather than as external linear multipliers of squared deviations. The corresponding relative proximity is

$$R_i(w) = \frac{D_i^-(w)}{D_i^+(w) + D_i^-(w)}, \quad i = 1, \dots, n. \quad (9)$$

The lower and upper bounds of the proximity interval are found from

$$R_i^L = \min_{w \in \Omega} R_i(w), \quad (10)$$

$$R_i^U = \max_{w \in \Omega} R_i(w). \quad (11)$$

The optimisation problems in (10) and (11) are non-convex because of the fractional Euclidean form of the proximity function. They are solved with sequential quadratic programming (SQP), using 30 random restarts for each alternative in order to reduce the chance of convergence to a local optimum.

The alternatives are ordered by the interval-based score:

$$S_i = k_1 R_i^L + k_2 R_i^U. \quad (12)$$

Here, k_1 and k_2 control the relative importance of the lower and upper bounds of the proximity interval. In the present study, both are set equal to one, so the two bounds receive the same importance. This follows the interval comparison principle of Cañós and Liern [18]. The role of that reference is limited to the interval-based ranking rule. The UW-TOPSIS distance and proximity formulation itself follows [14,15]. The ranking is produced in descending order of S_i . If two alternatives have the same score, the one with the larger R_i^L is preferred. In the current data, no exact ties in S_i scores occurred, so the tie-breaking rule was not needed.

Since

$$R_i(w) = \frac{1}{2} \iff D_i^-(w) = D_i^+(w),$$

the value $1/2$ is the relevant reference value for the proximity function. Therefore, when $k_1 = k_2 = 1$, the condition $S_i = R_i^L + R_i^U > 1$ is equivalent to requiring that the midpoint of the interval $[R_i^L, R_i^U]$ is greater than 0.5. In this study, this rule is used only for midpoint-based screening. It does not imply that $R_i(w) > 0.5$ for every $w \in \Omega$. The stronger condition would be $R_i^L > 0.5$.

3.2.1. Weight-Interval Scenarios

Four weight-interval scenarios are used in order to study how the ranking changes under different design priorities. Instead of fixing one weight for each criterion, each criterion is assigned an interval of admissible values. The first scenario uses equal intervals for all criteria and therefore represents a neutral case in which no sustainability dimension is favoured. The remaining three scenarios favour, respectively, the environmental, economic, and technical groups by assigning higher and wider intervals to the corresponding criteria.

Within a given scenario, all criteria in the same category receive the same interval. No criterion is assigned zero weight, so all criteria remain active in the analysis. The intervals

are chosen so that $\sum l_j \leq 1 \leq \sum u_j$, which guarantees that feasible weight vectors exist. The four scenarios are given in Table 5.

Table 5. Weight-interval scenarios used in the UW-TOPSIS analysis.

Scenario	Environmental	Cost	Technical	Description
Case 1	[0.03, 0.25]	[0.03, 0.25]	[0.03, 0.25]	Equal weight intervals
Case 2	[0.10, 0.25]	[0.08, 0.15]	[0.08, 0.15]	Environmental favoured
Case 3	[0.08, 0.15]	[0.10, 0.25]	[0.08, 0.15]	Cost favoured
Case 4	[0.08, 0.15]	[0.08, 0.15]	[0.10, 0.25]	Technical favoured

3.3. Stage 2: Objective Weighting and Standardised TOPSIS

After the UW-TOPSIS analysis, a reduced set of alternatives is selected from the balanced scenario (case 1). Stage 2 is applied to the alternatives that satisfy $S_i > 1$ in that scenario. Since $k_1 = k_2 = 1$, this means that the midpoint of $[R_i^L, R_i^U]$ is greater than 0.5. The condition is used here only as a screening rule. It does not mean that $R_i(w) > 0.5$ for every $w \in \Omega$. Under the balanced scenario, 12 alternatives satisfy this condition: S01–S08 and S13–S16. That is, all alternatives from groups G1, G2, and G4. The same set is also obtained under the environmental scenario (case 2), which shows that the selection does not change between these two more neutral weighting views.

The second stage applies a TOPSIS variant to this reduced set. Following the canonical formulation of Hwang and Yoon [19], both the objective weights and the Euclidean distances would be computed from the vector-normalised matrix **R**. Here, we depart from that single-normalisation scheme in one step only: vector normalisation is retained for weight computation, whereas Z-score standardisation is used at the distance step. The reason is not a difference in absolute scale, because Equation (3) has already rescaled every criterion column to unit Euclidean norm. The reason is a difference in dispersion. Vector normalisation is a positive column-wise rescaling and therefore preserves each criterion's coefficient of variation exactly: $CV(R_{\cdot j}) = CV(X_{\cdot j})$. Consequently, the squared deviations $(r_{ij} - r_j^\pm)^2$ that drive the Euclidean sum scale approximately with the square of the column-wise coefficient of variation, so criteria with small relative dispersion contribute very little to the distance. In the retained set, this produces a pronounced imbalance: the coefficients of variation range from 0.006 for material cost (C5) to 0.369 for end-of-life cost (C8), so a single criterion can dominate the Euclidean geometry. Z-score standardisation at the distance step rescales every column to unit variance and removes this dispersion-induced bias. Using the same normalisation throughout is not neutral either: if Z-score standardisation were used for weight computation, the SD method would collapse to equal weights and the COV method would become undefined because the column means would be zero. These degeneracies are avoided by keeping vector normalisation for the weighting step. The two normalisations therefore serve complementary purposes: **R** preserves the inter-criterion dispersion structure required by the weighting methods, while **Z** removes that structure from the distance computation, where it would otherwise bias the ranking toward high-dispersion criteria.

3.3.1. Vector Normalisation for Weight Computation

The objective weights are computed from the vector-normalised matrix **R** in Equation (3). This transformation rescales each criterion column to unit Euclidean norm while preserving the relative dispersion structure among columns: the coefficient of variation of criterion j is identical in **X** and in **R**. That dispersion information is exactly what dispersion-based methods (SD and COV) and contrast-based methods (CRITIC) require in order to assign weights. If Z-score standardisation were used at this step, each criterion

would be forced to zero mean and unit variance, and the information needed by these weighting schemes would be lost. In particular, the SD method would reduce to equal weights and the coefficient of variation would be undefined. Vector normalisation avoids these problems and keeps all column means strictly positive.

3.3.2. Z-Score Normalisation for TOPSIS Distance Computation

The TOPSIS distances are computed from Z-score-standardised data. The purpose is to equalise the dispersion of each criterion column so that no single criterion dominates the Euclidean sum by virtue of having a larger coefficient of variation than the others. Each criterion column is standardised as

$$z_{ij} = \frac{r_{ij} - \mu_j}{s_j}, \quad (13)$$

where μ_j and s_j are the mean and standard deviation of criterion j over the retained alternatives. Equation (13) is well-defined provided $s_j > 0$, which is the case for all criteria in the retained set. (Z-score standardisation is invariant under positive column-wise rescaling: if $\tilde{x}_{ij} = c_j x_{ij}$ with $c_j > 0$, then $\tilde{z}_{ij} = z_{ij}$. It therefore produces the same $\mathbf{Z}$ whether it is applied to $\mathbf{X}$ or to the vector-normalised matrix $\mathbf{R}$. The use of both $\mathbf{R}$ and $\mathbf{Z}$ reflects their different roles in the method: weight computation and distance computation, respectively.) After standardisation, every column has zero mean and unit variance, so the contribution of each criterion to $\sum_j (z_{ij} - z_j^\pm)^2$ is of comparable order before the weights are applied. Because all criteria are of the cost type and the transformation is strictly increasing within each criterion column, the ideal points in the Z-standardised space are

$$z_j^+ = \min_i z_{ij}, \quad z_j^- = \max_i z_{ij}, \quad j = 1, \dots, m. \quad (14)$$

The weighted matrix is $\mathbf{V} = \mathbf{Z} \cdot \text{diag}(w)$, with weighted ideal coordinates $v_j^\pm = w_j z_j^\pm$, and the TOPSIS distances are

$$D_i^+ = \left[\sum_{j=1}^m (v_{ij} - v_j^+)^2 \right]^{1/2}, \quad D_i^- = \left[\sum_{j=1}^m (v_{ij} - v_j^-)^2 \right]^{1/2}. \quad (15)$$

Z-score standardisation is applied only after the weights have been computed from the vector-normalised matrix $\mathbf{R}$. Thus, weight computation and distance computation are based on different matrices, $\mathbf{R}$ and $\mathbf{Z}$, because they serve different purposes. This dual-normalisation scheme departs from the canonical TOPSIS of Hwang and Yoon [19], where vector normalisation is used throughout; we therefore refer to it as standardised TOPSIS. The five objective weighting methods used in stage 2 are summarised in Table 6.

Table 6. Objective weighting methods and their main principles.

Method	Principle	Key Quantity
CRITIC	Criteria importance through inter-criteria correlation [20]	Contrast $\times$ conflict
SD	Standard deviation of criterion values [21,22]	Variability magnitude
COV	Coefficient of variation (ratio of SD to mean) [21]	Relative variability
Entropy	Shannon entropy of the normalised values [19,21]	Information content
MEREC	Removal effects of criteria [23,24]	Marginal contribution

For each retained alternative i , the TOPSIS closeness coefficient is

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-}, \quad (16)$$

where D_i^+ and D_i^- are the Euclidean distances defined in Equation (15). The final ranking is obtained in descending order of C_i .

4. Results

4.1. Sustainability Criteria Results and Decision Matrix

The LCA and LCC calculations were carried out for all 24 tank configurations. Together with the technical criterion, namely, mass, they provide the values of the nine sustainability criteria used in the analysis. The resulting decision matrix is given in Table 7.

Table 7. Decision matrix for LH₂ tank alternatives. All criteria are of the cost (minimise) type.

ID	C1 (DALYs)	C2 (sp-yr)	C3 (USD)	C4 (kg CO ₂)	C5 (EUR)	C6 (EUR)	C7 (EUR)	C8 (EUR)	C9 (kg)
S01	0.034963	4.46×10^{-5}	1436.226	9643.232	45,228.50	490.207	0.026151	110.594	882.080
S02	0.035153	4.49×10^{-5}	1440.617	9710.437	45,242.71	492.786	0.026297	113.064	887.020
S03	0.035448	4.54×10^{-5}	1447.438	9814.850	45,264.79	496.792	0.026525	116.902	894.696
S04	0.035637	4.57×10^{-5}	1451.829	9882.055	45,279.00	499.371	0.026671	119.372	899.636
S05	0.041705	5.60×10^{-5}	1591.718	12,029.780	45,729.93	581.199	0.031318	197.778	1056.387
S06	0.041895	5.64×10^{-5}	1596.109	12,096.990	45,744.14	583.778	0.031465	200.248	1061.327
S07	0.042190	5.69×10^{-5}	1602.930	12,201.400	45,766.22	587.784	0.031692	204.086	1069.003
S08	0.042379	5.72×10^{-5}	1607.321	12,268.610	45,780.43	590.363	0.031839	206.556	1073.943
S09	0.050248	7.87×10^{-5}	2183.004	17,360.950	48,593.78	559.916	0.037372	57.282	1260.578
S10	0.050438	7.90×10^{-5}	2187.395	17,428.150	48,607.99	562.495	0.037518	59.752	1265.519
S11	0.050733	7.95×10^{-5}	2194.217	17,532.570	48,630.07	566.502	0.037746	63.590	1273.194
S12	0.050922	7.98×10^{-5}	2198.607	17,599.770	48,644.28	569.081	0.037892	66.060	1278.134
S13	0.030443	3.93×10^{-5}	1467.045	8389.118	45,829.75	554.184	0.032347	296.689	1091.086
S14	0.030633	3.96×10^{-5}	1471.435	8456.324	45,843.96	556.763	0.032493	299.160	1096.027
S15	0.030928	4.01×10^{-5}	1478.257	8560.736	45,866.04	560.769	0.032721	302.997	1103.702
S16	0.031117	4.04×10^{-5}	1482.647	8627.942	45,880.25	563.348	0.032867	305.467	1108.642
S17	0.037185	5.08×10^{-5}	1622.537	10,775.670	46,331.18	645.176	0.037515	383.873	1265.393
S18	0.037375	5.11×10^{-5}	1626.927	10,842.870	46,345.39	647.755	0.037661	386.343	1270.334
S19	0.037670	5.16×10^{-5}	1633.749	10,947.290	46,367.47	651.761	0.037889	390.181	1278.009
S20	0.037860	5.19×10^{-5}	1638.140	11,014.490	46,381.68	654.340	0.038035	392.651	1282.949
S21	0.045728	7.34×10^{-5}	2213.823	16,106.840	49,195.03	623.893	0.043568	243.377	1469.585
S22	0.045918	7.38×10^{-5}	2218.214	16,174.040	49,209.24	626.472	0.043715	245.848	1474.525
S23	0.046213	7.43×10^{-5}	2225.035	16,278.450	49,231.32	630.479	0.043942	249.685	1482.200
S24	0.046402	7.46×10^{-5}	2229.426	16,345.660	49,245.53	633.057	0.044089	252.155	1487.140

The entries in Table 7 show that the alternatives differ noticeably across several criteria. Criterion C1 (human health) varies from 0.030 to 0.051 DALYs, while criterion C4 (global warming potential) ranges from about 8400 to 17,600 kg CO₂ eq. In both cases, the spread is greater than a factor of two over the whole design space. These differences are mainly associated with the selected materials, the corresponding manufacturing routes, and the assumed end-of-life treatment. The economic criteria C5–C8 vary less in absolute terms, although C8 (end-of-life cost) spans almost two orders of magnitude, from about 57 to 393 EUR. This variation is mainly driven by differences in total mass and material composition across the configurations, with lighter aluminium-based configurations leading

to lower end-of-life costs, while configurations including CFRP exhibit reduced contributions due to the low unit cost assumed for landfill. By contrast, C2 (ecosystems) and C3 (resources) are comparatively less dispersed. The technical criterion, mass, ranges from about 882 kg for S01 to 1487 kg for S24, and this is mainly explained by the density of the structural materials used in each configuration.

4.2. Sustainability Ranking Using UW-TOPSIS

4.2.1. Balanced Weight Scenario

We first examine the balanced weighting scenario (case 1), which serves as the base-line case. Table 8 reports the lower and upper bounds of the proximity intervals, the corresponding score values, and the resulting ranks.

Table 8. UW-TOPSIS proximity intervals under the balanced scenario (case 1), ranked by the Canós–Liern score ($k_1 = k_2 = 1$).

Rank	Alt.	Group	R^L	R^U	Score	Width
1	S01	G1	0.8220	0.9631	1.7851	0.1412
2	S02	G1	0.8140	0.9605	1.7744	0.1465
3	S03	G1	0.8013	0.9541	1.7554	0.1528
4	S04	G1	0.7931	0.9491	1.7422	0.1560
5	S13	G4	0.3241	0.9020	1.2261	0.5779
6	S05	G2	0.4910	0.7317	1.2228	0.2407
7	S14	G4	0.3168	0.9000	1.2168	0.5832
8	S06	G2	0.4812	0.7248	1.2060	0.2435
9	S15	G4	0.3054	0.8960	1.2014	0.5906
10	S16	G4	0.2981	0.8929	1.1911	0.5948
11	S07	G2	0.4662	0.7140	1.1802	0.2478
12	S08	G2	0.4566	0.7071	1.1637	0.2505
13	S09	G3	0.1361	0.8580	0.9941	0.7219
14	S10	G3	0.1333	0.8549	0.9882	0.7216
15	S11	G3	0.1295	0.8496	0.9791	0.7201
16	S12	G3	0.1275	0.8458	0.9733	0.7183
17	S17	G5	0.0956	0.7039	0.7994	0.6083
18	S18	G5	0.0923	0.6973	0.7897	0.6050
19	S19	G5	0.0883	0.6868	0.7752	0.5985
20	S20	G5	0.0865	0.6802	0.7667	0.5938
21	S21	G6	0.0880	0.4277	0.5158	0.3397
22	S22	G6	0.0844	0.4203	0.5047	0.3359
23	S23	G6	0.0797	0.4088	0.4886	0.3291
24	S24	G6	0.0774	0.4015	0.4789	0.3241

The first four positions are occupied by S01–S04, all from group G1, that is, the configurations with Al2219-T8 in both the outer and inner tanks. Their intervals are not only high but also relatively narrow. In particular, R^L lies roughly between 0.79 and 0.82, R^U between 0.95 and 0.96, and the width stays between about 0.14 and 0.16. Within the balanced scenario, this combination of high scores and limited width suggests that these four alternatives are less sensitive to admissible changes in the weights than the remaining groups.

Ranks 5–12 are shared by two interleaved groups, G4 and G2, but their interval profiles are different. The G4 alternatives (S13–S16, steel outer tank and aluminium inner tank) reach higher upper bounds, close to 0.90, while their lower bounds remain much smaller, around 0.30–0.32. Their intervals are therefore wide. The G2 alternatives (S05–S08,

aluminium outer tank and steel inner tank) have lower upper bounds, around 0.71–0.73, but clearly higher lower bounds, around 0.46–0.49, and thus narrower intervals. This difference matters in practice. If more emphasis is placed on the lower bound, G2 appears preferable; if attention shifts to the upper bound, G4 becomes more attractive.

The four G3 alternatives (S09–S12) behave differently again. Their lower bounds are very small, around 0.13–0.14, whereas their upper bounds remain fairly high, around 0.85–0.86. As a result, they have the widest intervals in the whole table, close to 0.72. This indicates that these CFRP-based inner-tank configurations look competitive only for a more limited part of the admissible weighting region and are therefore much less stable when preferences are not fixed.

The bottom of the ranking is occupied by groups G5 and G6. Their score values are low, and their upper bounds leave less room for improvement than in the other groups. The same pattern can be seen in the R^L – R^U plane in Figure 3.

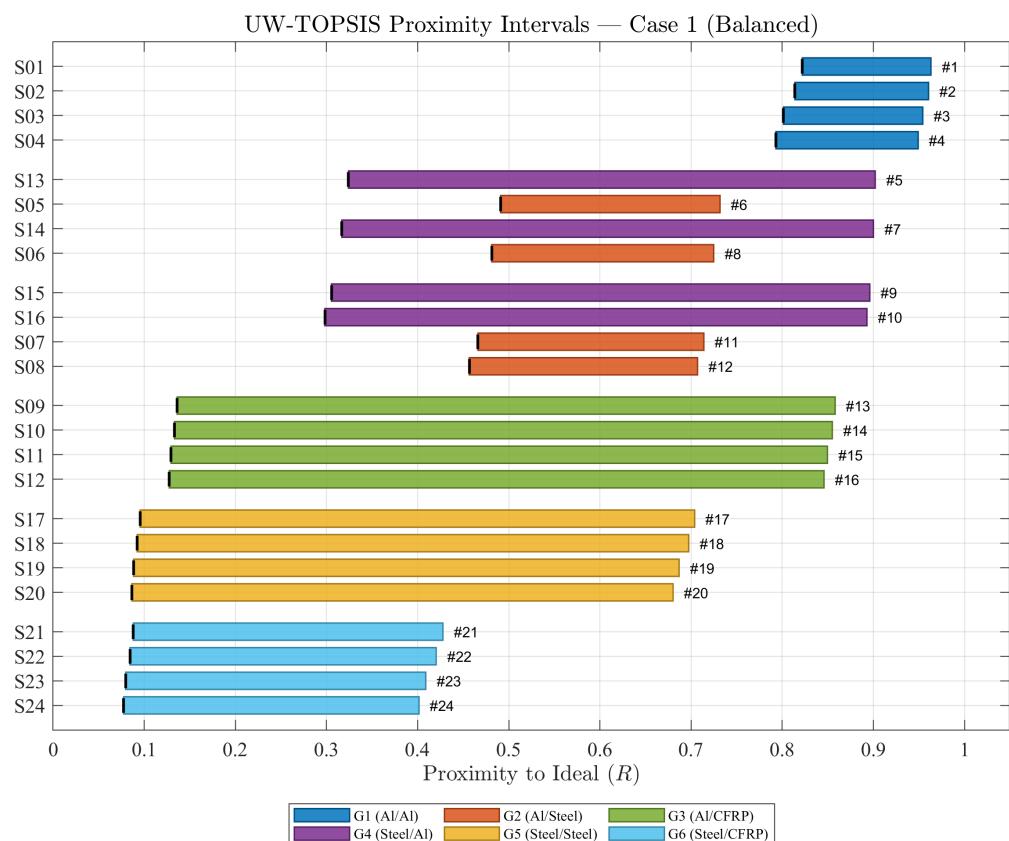


Figure 3. UW-TOPSIS proximity intervals for the LH₂ tank design alternatives in the balanced scenario (case 1). The alternatives are arranged by material group (G1–G6) and, within each group, by rank. Each horizontal bar shows the interval $[R_i^L, R_i^U]$.

4.2.2. Preference Scenarios

To examine how the ranking changes when the design priorities change, the same UW-TOPSIS procedure was applied to three additional scenarios: environmental preference (case 2), cost preference (case 3), and technical preference (case 4). The resulting ranks are reported in Table 9 and shown in Figure 4.

Table 9. Ranks of the LH₂ tank configurations under the four weighting scenarios. Alternatives marked with * keep the same rank in all scenarios.

Alt.	Group	Balanced	Env.	Cost	Tech.	Range
S01	G1	1	1	1	1	0 *
S02	G1	2	2	2	2	0 *
S03	G1	3	3	3	3	0 *
S04	G1	4	4	4	4	0 *
S05	G2	6	7	8	5	3
S06	G2	8	9	10	6	4
S07	G2	11	11	11	7	4
S08	G2	12	12	12	8	4
S09	G3	13	13	5	13	8
S10	G3	14	14	6	14	8
S11	G3	15	15	7	15	8
S12	G3	16	16	9	16	7
S13	G4	5	5	13	9	8
S14	G4	7	6	14	10	8
S15	G4	9	8	15	11	7
S16	G4	10	10	16	12	6
S17	G5	17	17	20	17	3
S18	G5	18	18	22	18	4
S19	G5	19	19	23	19	4
S20	G5	20	20	24	20	4
S21	G6	21	21	17	21	4
S22	G6	22	22	18	22	4
S23	G6	23	23	19	23	4
S24	G6	24	24	21	24	3

One point is unchanged across all four scenarios: S01–S04 remain in ranks 1–4. At the level of the scenarios examined here, this shows that group G1 stays at the top whether environmental, cost, or technical criteria are favoured. This is not a proof of pairwise dominance over the full admissible weight region, but it is consistent with the strong overall performance of Al2219-T8 across the nine criteria considered in this study.

The middle part of the ranking changes much more. Group G3 provides the clearest example. In the balanced scenario, S09–S12 are in ranks 13–16, whereas in the cost-favoured scenario they move up to ranks 5–9. This shift is consistent with the more favourable cost profile of the CFRP-based inner-tank options under that scenario. Group G4 moves in the other direction. It remains competitive in the balanced and environmental cases, but drops when cost is given greater emphasis, which is consistent with the higher material and processing cost associated with the stainless-steel outer tank.

The same overall picture is visible at the group level in Table 10.

Table 10. Rank stability of material groups across weight scenarios.

Group	Material (Outer/Inner)	Best	Worst	Avg.	Range	Stability
G1	Al/Al	1	4	2.5	3	Stable
G2	Al/steel	5	12	8.9	7	Moderate
G3	Al/CFRP	5	16	12.6	11	Variable
G4	Steel/Al	5	16	10.0	11	Variable
G5	Steel/steel	17	24	19.4	7	Moderate
G6	Steel/CFRP	17	24	21.6	7	Moderate

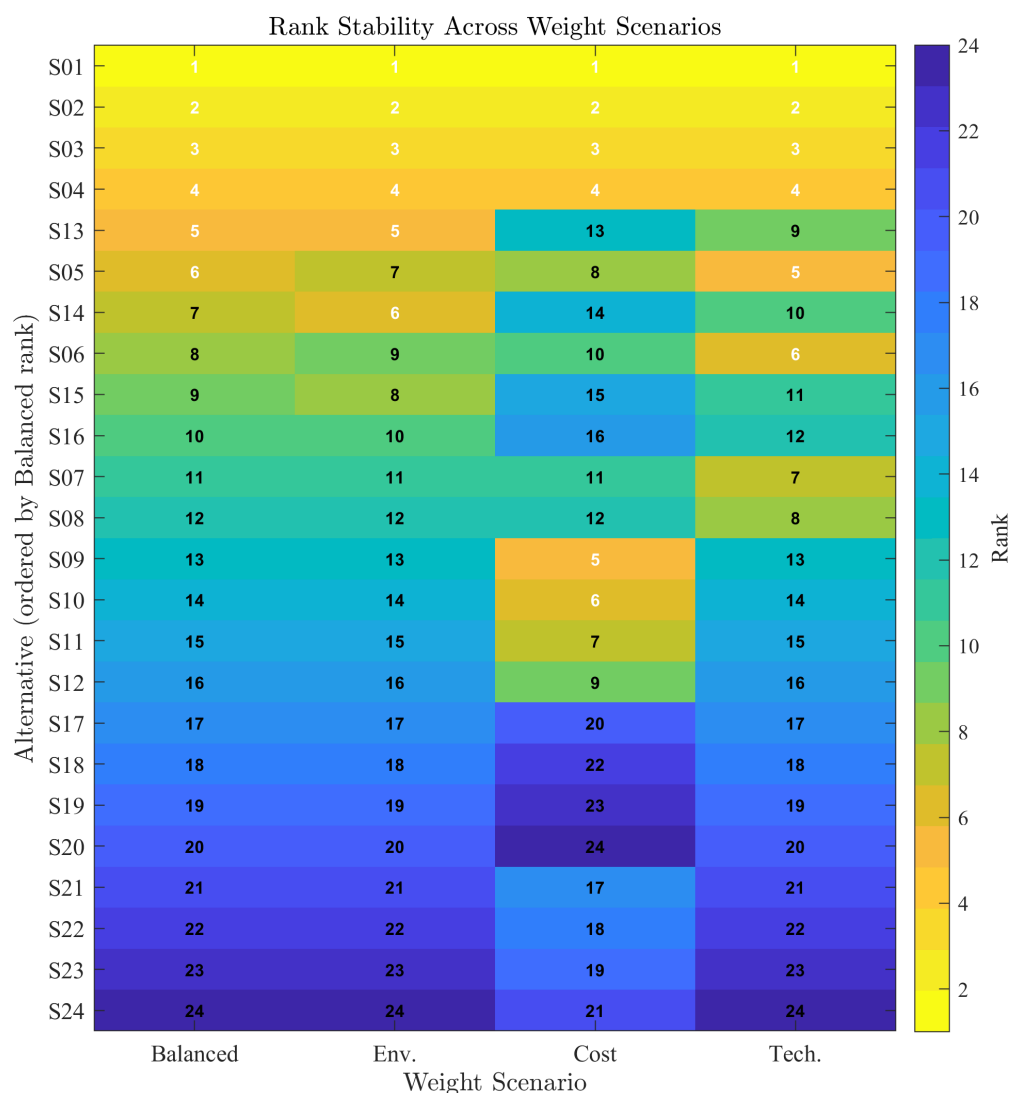


Figure 4. Heatmap of LH₂ tank alternative rankings across four weighting scenarios. Darker shading indicates better (lower) rank. Alternatives are ordered by their balanced-scenario rank.

For completeness, the proximity-interval plots for cases 2–4 are given in Figures 5–7, while the corresponding numerical values are reported in Appendix C.

The score values also make the screening rule easier to read. When $k_1 = k_2 = 1$, the Canós–Liern score is $S_i = R_i^L + R_i^U$, so the condition $S_i > 1$ simply means that the midpoint of $[R_i^L, R_i^U]$ is above 0.5. In the balanced scenario, 12 alternatives satisfy this condition, namely, all members of groups G1, G2, and G4. The numerical break between ranks 12 and 13 is clear: $S_{08} = 1.164$, whereas $S_{09} = 0.994$, so the gap is 0.170. The environmental scenario gives the same set of 12 alternatives, with a slightly larger gap of 0.174.

The cost-favoured scenario changes the boundary. Group G3 moves above the threshold, and S09 rises to rank 5 with $S_{09} = 1.225$. At the same time, group G4 becomes weaker, with S13 only just above the threshold at $S_{13} = 1.008$. The number of alternatives satisfying $S_i > 1$ therefore increases to 13. In the technical scenario, the threshold is less useful as a screening device, because all 16 alternatives from groups G1–G4 satisfy $S_i > 1$. There, the clearer separation is between ranks 16 and 17, where the score gap is $\Delta = 0.252$.

Taken together, these results support the same interpretation as the rank tables. Group G3 benefits from cost-oriented assumptions, while group G4 depends more on balanced or environmental emphasis. By contrast, the balanced and environmental scenarios, which are the two more neutral views in the present setting, identify the same

12 alternatives. For this reason, the balanced case is retained as the basis for passing alternatives to stage 2, namely, S01–S08 and S13–S16.

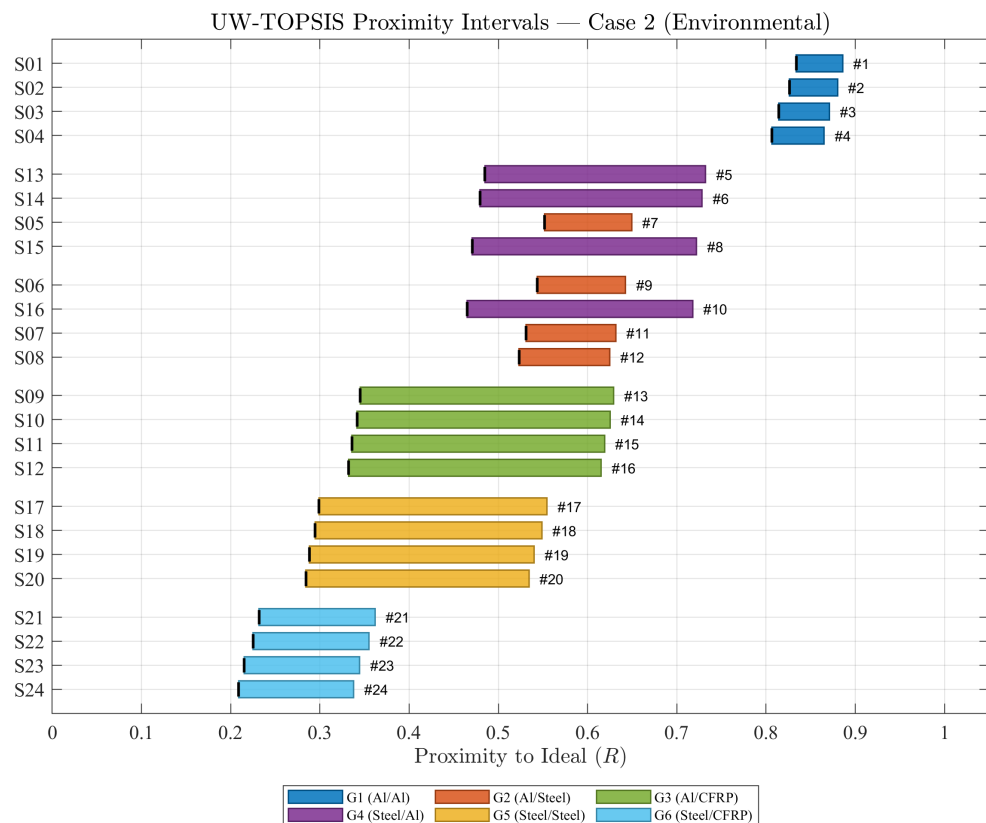


Figure 5. UW-TOPSIS proximity intervals under the environmental scenario (case 2).

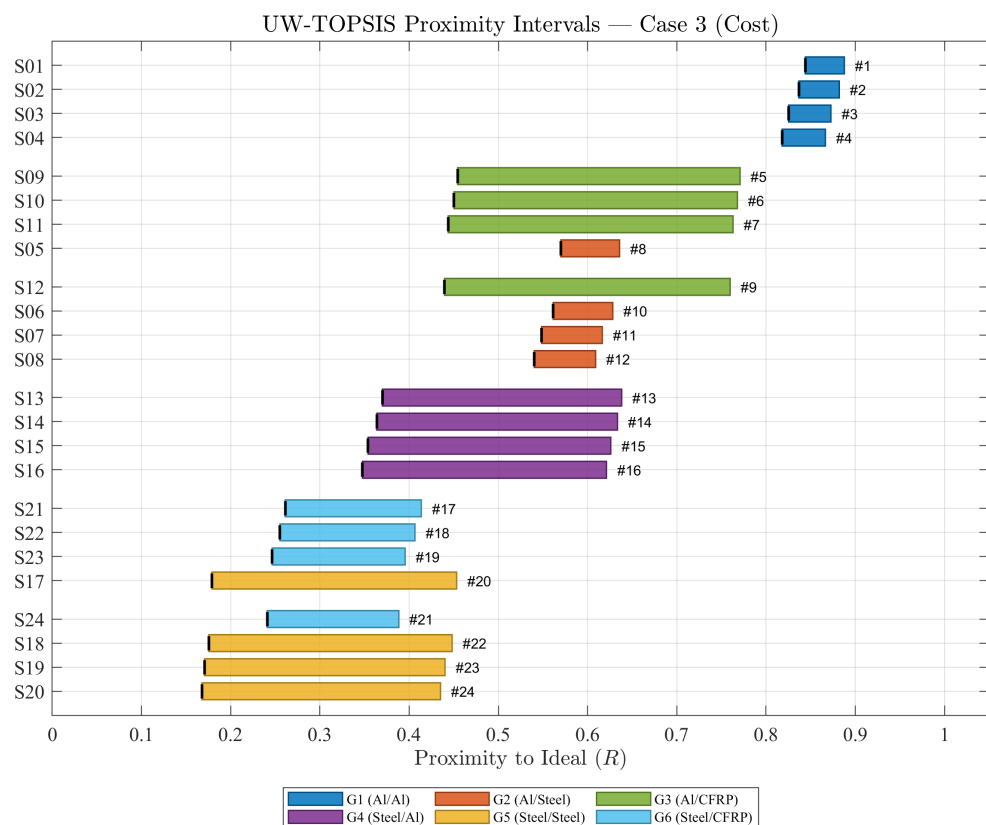


Figure 6. UW-TOPSIS proximity intervals under the cost scenario (case 3).

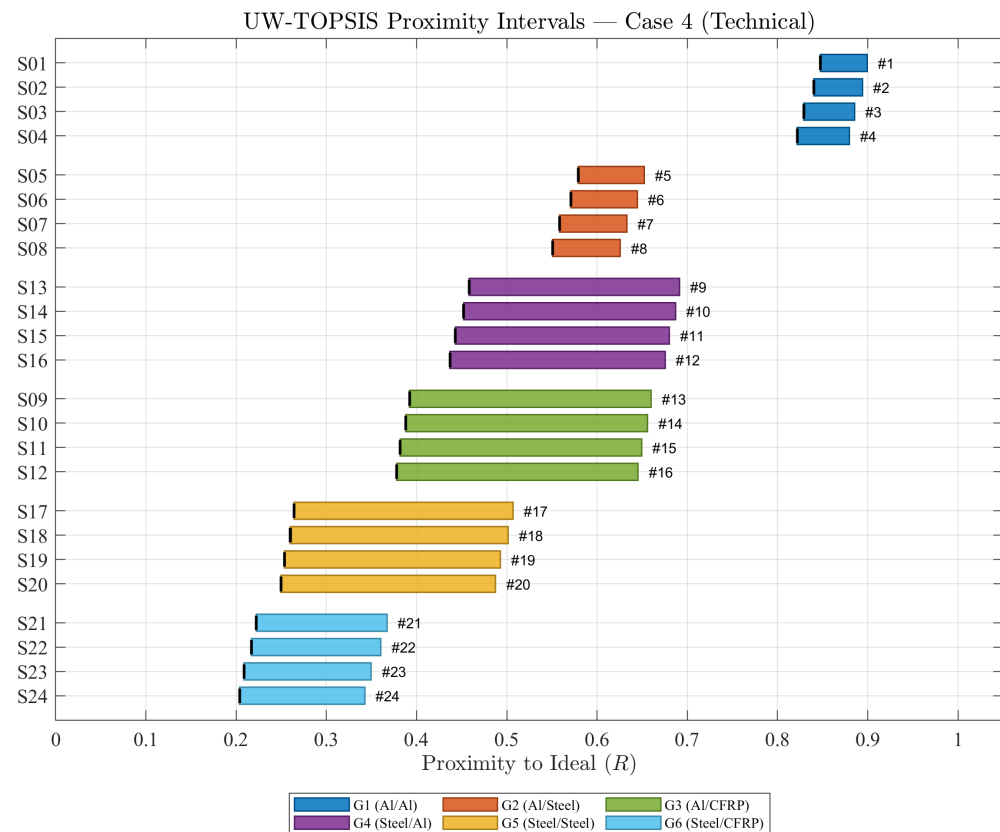


Figure 7. UW-TOPSIS proximity intervals under the technical scenario (case 4).

4.3. Stage 2: Objective Weighting and Standardised TOPSIS Ranking

Stage 2 reconsiders the reduced set of 12 alternatives with the standardised TOPSIS variant introduced in Section 3.3. At this point, the weights are no longer interval-valued. Instead, they are obtained directly from the reduced decision matrix by five objective weighting methods. The corresponding weight vectors, computed from the vector-normalised matrix of the retained alternatives, are shown in Table 11.

Table 11. Objective weights from five methods, computed on the vector-normalised matrix of the reduced top-12 set.

Method	C1	C2	C3	C4	C5	C6	C7	C8	C9	Max/Min
CRITIC	0.1354	0.1410	0.0254	0.1464	0.0042	0.0342	0.0644	0.3846	0.0644	92.6
SD	0.1194	0.1376	0.0419	0.1381	0.0054	0.0655	0.0839	0.3243	0.0839	59.9
COV	0.1173	0.1355	0.0409	0.1361	0.0053	0.0640	0.0821	0.3368	0.0821	63.9
Entropy	0.1184	0.1277	0.1393	0.1236	0.0942	0.0927	0.0942	0.1158	0.0942	1.5
MEREC	0.1087	0.1060	0.1259	0.1052	0.1747	0.1047	0.1002	0.0744	0.1002	2.3

As Table 11 shows, the five methods do not produce the same weight profile. The dispersion-based methods, namely, CRITIC, SD, and COV, concentrate their largest weight on criterion C8, the end-of-life cost. Their max/min ratios range from 59.9 to 92.6. This pattern is consistent with the much larger relative spread of end-of-life costs within the selected set, compared with the spread of material cost. In the present data, this is primarily associated with variations in overall mass and material distribution across the configurations. Material cost, by contrast, varies much less and therefore receives the lowest weight under these methods. The information-based methods, Entropy and MEREC, are much flatter, with max/min ratios of 1.5 and 2.3. The corresponding objective weight profiles are presented in Figure 8.

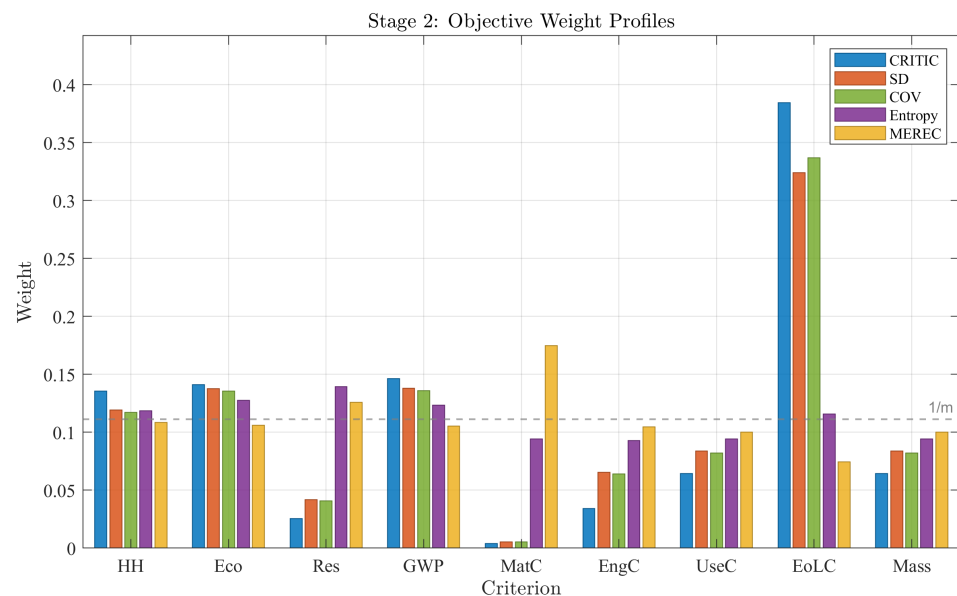


Figure 8. Stage 2 objective weight profiles from five methods. The dashed line indicates equal weighting ($1/m$). Dispersion-based methods (CRITIC, SD, COV) concentrate weight on C8 (EoL cost); information-based methods (Entropy, MEREC) distribute weight more uniformly.

Even with these differences, the rankings obtained in stage 2 agree very strongly at the top. The results are listed in Table 12.

All five methods place S01–S04 in ranks 1–4. This remains true even though the weighting rules are quite different. Within the reduced decision matrix used in stage 2, group G1 therefore keeps the leading positions under all five methods.

Below rank 4, the ordering is less consistent. CRITIC gives slightly better positions to group G2, especially at ranks 5 and 6, whereas the other four methods place group G4 ahead. This difference is linked mainly to criterion C8. Under CRITIC, end-of-life cost receives a particularly large weight, so the G4 alternatives, which use stainless steel in the outer tank, are penalised more strongly. When the weights are more evenly distributed, as in Entropy and MEREC, the environmental advantage of G4 is reflected more clearly and that group moves upward.

Table 12. Stage 2 standardised TOPSIS rankings under five objective weighting methods.

Alt.	Group	CRITIC	SD	COV	Entropy	MEREC	Consensus
S01	G1	1	1	1	1	1	1 (5/5)
S02	G1	2	2	2	2	2	2 (5/5)
S03	G1	3	3	3	3	3	3 (5/5)
S04	G1	4	4	4	4	4	4 (5/5)
S05	G2	5	8	6	9	9	9 (2/5)
S06	G2	6	10	8	10	10	10 (3/5)
S07	G2	8	11	11	11	11	11 (4/5)
S08	G2	10	12	12	12	12	12 (4/5)
S13	G4	7	5	5	5	5	5 (4/5)
S14	G4	9	6	7	6	6	6 (3/5)
S15	G4	11	7	9	7	7	7 (3/5)
S16	G4	12	9	10	8	8	8 (2/5)

The corresponding TOPSIS proximity scores are shown in Figure 9.

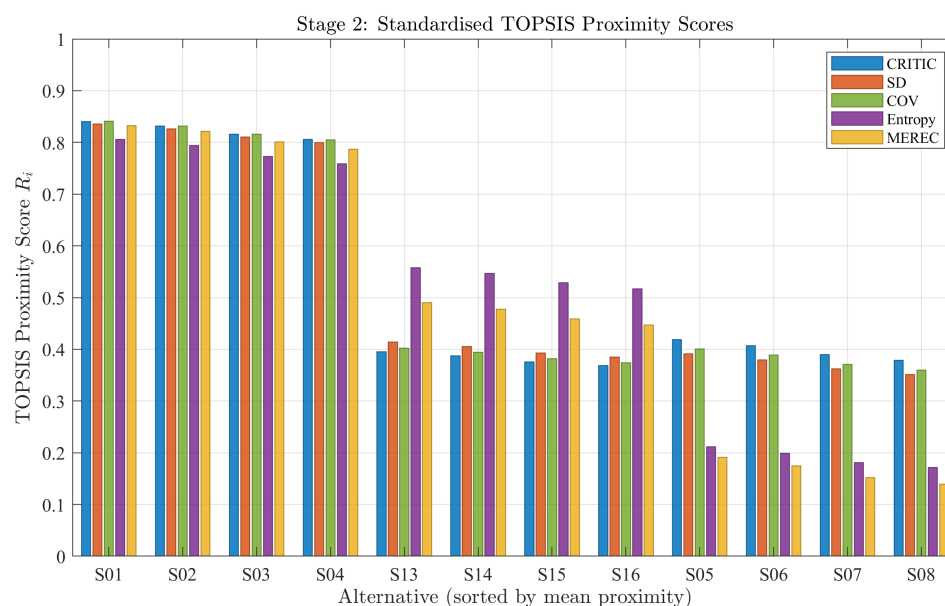


Figure 9. Stage 2 standardised TOPSIS proximity scores on the reduced top-12 set under five objective weighting methods.

5. Discussion

The two-stage analysis gives a rather stable picture of the LH₂ tank alternatives. Group G1 (S01–S04, all-aluminium) remains in ranks 1–4 in all stage 1 weighting scenarios and under all five objective weighting methods in stage 2. This level of agreement is not typical in multi-criteria studies, although the claim should be understood only within the set of scenarios and weighting methods examined here.

Table 13 presents a component-contribution breakdown for the top-performing configuration S01. The results show that the insulation systems represent major fixed contributions to both the environmental and economic criteria, particularly during the production stage. However, since the insulation and auxiliary systems remain unchanged across all investigated alternatives, they do not significantly influence the comparative ranking trends. The main ranking differences are instead driven by the varying inner- and outer-tank structures, which represent the dominant changing structural masses. In addition, the recyclability of the metallic structural components leads to negative end-of-life GWP values, contributing to lower overall environmental impacts for the aluminium-dominated configurations. The support structures have a secondary influence because of their lower mass contribution. The mass distribution of the S01 configuration is presented separately in Appendix B (Table A5), since mass is used as the technical criterion and is directly related to the use-phase impacts through the hydrogen consumption required for the transportation of the tank during the aircraft lifetime. For this reason, the use-phase contribution is not included in the component breakdown presented in Table 13. The presented contribution values reflect the modelling assumptions, system boundaries, and inventory data adopted in the present comparative assessment framework. However, the final selection of tank materials also depends on broader engineering and certification considerations, while the present framework is intended to support the comparative sustainability evaluation of the investigated design alternatives. The observed behaviour explains why the leading group remains stable across the investigated weighting settings. Nevertheless, this does not represent a formal proof of pairwise dominance over the full admissible weight region, but rather an interpretation of the ranking trends obtained under the assumptions and scenarios examined in the present study.

Table 13. Environmental impact and cost of system components.

Component	GWP Related to Production (kg CO ₂ eq.)	GWP Related to Disposal (kg CO ₂ eq.)	Cost (€)
Outer tank	1940	−3880	7197
Inner tank	1700	−3260	1726
Outer-tank supports	117	−234	82.33
Inner-tank supports	105	−85.6	133.91
External insulation	1180	111	15,000
Internal insulation	4660	74.4	21,600

One reason for this behaviour is the specific strength of Al2219-T8 (158.45 MPa · cm³/g), which is more than twice that of AISI 316L. In the present design space, this leads to a lower tank mass among the metallic options. A lower mass means lower hydrogen demand during the use phase, and that effect is reflected in both environmental and cost-related criteria. In the current decision matrix, all evaluated criteria are influenced by mass, which drives the differences observed across the configurations. For the cases studied here, this creates a cumulative advantage for group G1.

A second issue is the relation among the criteria. The framework is organised by outcome categories, not by statistical independence. Each criterion has its own role in the LCA/LCC setting, but some are connected through common underlying factors. In particular, mass (C9) influences both the use-phase behaviour and the material- and process-related impacts across the system. The nine criteria should therefore not be interpreted as fully independent dimensions. This is not a modelling flaw; it follows from the physical fact that lighter tanks require less material and less hydrogen in operation. Even so, the effect of this dependence should be kept in mind. A useful follow-up would be to test whether the ranking remains the same under a reduced or decorrelated set of criteria, for example, by removing C9 or one criterion that is strongly driven by mass.

The use of two different normalisation steps in stage 2 also needs a brief explanation. It was not introduced for convenience. Vector normalisation was kept for weight computation because the objective weighting methods must still see the original variation across criteria. If Z-score standardisation were used at that stage, every criterion would have zero mean and unit variance, and the information needed by SD, COV, and CRITIC would be lost. Then, the SD method would reduce to equal weights, and the COV method would be undefined. Vector normalisation, by contrast, keeps the column means positive and preserves the dispersion structure required by these methods. This also explains why the dispersion-based methods assign the largest weight to C8. In the reduced set, end-of-life cost varies much more than material cost, which is linked to the different end-of-life treatment of aluminium and steel.

The middle part of the ranking depends more strongly on the weighting assumptions. This is exactly where UW-TOPSIS is useful. Group G3 (S09–S12, Al/CFRP) moves from ranks 13–16 in the balanced case to ranks 5–9 when cost is favoured. This shift is mainly associated with the lower material cost of the CFRP-based option. Group G4 (S13–S16, steel/Al) moves in the opposite direction. It stays competitive in the balanced and environmental cases, but drops when cost receives greater emphasis. Under a single fixed-weight ranking, this contrast between G3 and G4 would be much less visible. Here, it is seen directly through the interval-based analysis.

The stage 2 weight vectors may look uneven, especially for the dispersion-based methods. For CRITIC, the ratio between the largest and smallest weight reaches 92.6. That is large, but in the present data it reflects a property of the reduced set rather than a numerical artefact. End-of-life cost shows much stronger relative variation than some

other criteria, and the weighting methods that respond to dispersion pick up exactly that feature. Entropy and MEREC are flatter by construction, yet they still produce the same top four alternatives. Under the current modelling assumptions, this agreement supports the stability of the leading group.

The analysis also has clear limits. The results depend on the life-cycle inventory, the chosen system boundaries, and the modelling assumptions used throughout the study. This is especially true for the use-phase model, where hydrogen demand is linked to mass through the Piaggio P.180 reference aircraft. A different aircraft, mission profile, or hydrogen supply pathway could change the strength of the mass-related advantage observed here. The technical side of the problem is represented only by mass. Other important properties, such as hydrogen permeability, cryogenic durability, inspectability, damage tolerance, and thermal performance, are discussed in the introduction but are not included as explicit criteria. The comparison is also limited to metallic and CFRP solutions; other candidate materials, such as thermoplastic composites or aluminium–lithium alloys, are outside the scope of the present work. The obtained results are therefore specific to the investigated baseline tank configuration and the selected design space. In addition, no formal propagation of uncertainty from the LCA/LCC inputs to the decision matrix has been carried out, no sensitivity study has been performed for alternative stage 1 normalisation choices, and the social dimension of sustainability has not been included.

6. Conclusions

This study proposed a two-stage multi-criteria framework for the sustainability assessment of liquid hydrogen aircraft tank configurations. In the first stage, UW-TOPSIS was used to examine the design space under interval-valued weights, without assuming fixed preferences in advance. In the second stage, the reduced set of alternatives was re-evaluated with a standardised TOPSIS variant (vector-normalised weights, Z-standardised distances) and five objective weighting methods.

A clear result was observed in all analyses carried out here. The all-aluminium configurations S01–S04 (group G1) remained in ranks 1–4 in all four weighting scenarios and under all five objective weighting methods. Thus, the same top four alternatives were obtained in nine separate evaluations. The middle part of the ranking was less stable. Mixed-material configurations changed position by as many as eight ranks across the scenarios, which shows that their evaluation depends much more strongly on the adopted design priorities. From the methodological side, the use of vector normalisation for weight computation and Z-score normalisation for distance computation was necessary. A single normalisation scheme would have produced known problems, including degenerate SD weights and an undefined COV method.

The framework is intended for cases in which criterion weights cannot yet be justified at the start of the analysis. The final ranking is then obtained only after the reduced set has been identified and the weights have been derived from its decision matrix. Future work may extend the comparison to additional structural materials, include further technical criteria such as thermal performance, and incorporate the social dimension of sustainability.

Author Contributions: Conceptualization, A.A., D.G.S., and K.T.; methodology, A.A., D.G.S., K.T., G.T., and G.L.; software, A.A. and D.G.S.; validation, A.A., D.G.S., K.T., G.T., and G.L.; formal analysis, A.A., D.G.S., and K.T.; investigation, A.A., D.G.S., K.T., G.T., and G.L.; resources, K.T. and G.L.; data curation, A.A., D.G.S., K.T., G.T., K.F., and G.L.; writing—original draft preparation, A.A. and D.G.S.; writing—review and editing, A.A., D.G.S., K.T., G.T., K.F., and G.L.; supervision, K.T. and G.L.; project administration, K.T. and G.L.; funding acquisition, K.T. and G.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by the Horizon Europe Clean Aviation Project H2ELIOS, grant number 101102003.

Data Availability Statement: All data supporting the findings of this study are contained within the article and its appendices.

Acknowledgments: The H2ELIOS cryogenic tank concept for storing liquid hydrogen is patent protected under a patent owned by Aciturri.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

LH ₂	Liquid hydrogen
LCA	Life-cycle assessment
LCC	Life-cycle costing
LCI	Life-cycle inventory
MCDM	Multi-criteria decision making
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
UW-TOPSIS	Unweighted TOPSIS
CRITIC	Criteria Importance Through Intercriteria Correlation
SD	Standard deviation
COV	Coefficient of variation
MEREC	Method Based on the Removal Effects of Criteria
CFRP	Carbon fibre-reinforced polymer
GFRP	Glass fibre-reinforced polymer
PTFE	Polytetrafluoroethylene
GWP	Global warming potential
SAF	Sustainable aviation fuel
PIS	Positive ideal solution
NIS	Negative ideal solution
SQP	Sequential quadratic programming

Appendix A. Material Alternatives for Tank Components

The material combinations for the four variable structural components are summarised in Tables A1–A4. Each table lists the candidate materials at the subcomponent level. Common materials (e.g., PTFE liners, BaSO₄ seals, GFRP spacers) appear in every alternative and are therefore not treated as design variables; they are, however, included in all environmental, economic, and technical calculations.

Table A1. Inner-tank alternatives.

Inner-Tank A	Inner-Tank B	Inner-Tank C
AISI 316L stainless steel	Al2219-T8	PC + 20 wt% CF
PTFE (polytetrafluoroethylene)	PTFE (polytetrafluoroethylene)	PTFE (polytetrafluoroethylene)
BaSO ₄	BaSO ₄	BaSO ₄

Table A2. Inner-tank support alternatives.

Inner-Tank Supports A	Inner-Tank Supports B
Spring steel 17-4PH	Spring steel 17-4PH
AISI 316L stainless steel	Al2219-T8
GFRP	GFRP

Table A3. Outer-tank support alternatives.

Outer-Tank Supports A	Outer-Tank Supports B
AISI 316L stainless steel	Al2219-T8

Table A4. Outer-tank alternatives.

Outer-Tank A	Outer-Tank B
UD tape CFRP	UD tape CFRP
Fabric CFRP	Fabric CFRP
PTFE (polytetrafluoroethylene)	PTFE (polytetrafluoroethylene)
BaSO ₄	BaSO ₄
AISI 316L stainless steel (auxiliary)	Al2219-T8 (auxiliary)
AISI 316L stainless steel (welded elements)	Al2219-T8 (welded elements)
AISI 316L stainless steel (systems assembly)	Al2219-T8 (systems assembly)

Appendix B. Mass Distribution

Table A5 presents the mass distribution per component for the reference scenario (scenario 1), in which Al2219-T8 is the baseline material for all main structural components.

Table A5. Mass distribution per component for the reference scenario (scenario 1).

Component	Material	Mass (kg)
Outer tank	Al2219-T8	177.51
	UD tape CFRP	65.00
	Fabric CFRP	10.60
	PTFE BaSO ₄	1.599
Inner tank	Al2219-T8	148.04
	PTFE BaSO ₄	0.84
Outer-tank supports	Al2219-T8	10.71
	Al2219-T8	4.196
Inner-tank supports	Spring steel 17-4PH	14.867
	GFRP	0.237
External insulation	Closed-cell insulation material	268.26
Internal insulation	Open-cell insulation material	180.21

Appendix C. UW-TOPSIS Proximity Intervals for Cases 2–4

Tables A6–A8 present the complete UW-TOPSIS proximity intervals under the environmental, cost, and technical scenarios, respectively. These tables complement the balanced-scenario results in Table 8 and underpin the cross-case comparison of Table 9.

Table A6. UW-TOPSIS proximity intervals under the environmental scenario (case 2).

Rank	Alt.	Group	R^L	R^U	Score	Width
1	S01	G1	0.8337	0.8860	1.7197	0.0522
2	S02	G1	0.8262	0.8803	1.7064	0.0541
3	S03	G1	0.8143	0.8710	1.6853	0.0567
4	S04	G1	0.8066	0.8650	1.6716	0.0583

Table A6. Cont.

Rank	Alt.	Group	R^L	R^U	Score	Width
5	S13	G4	0.4850	0.7321	1.2170	0.2471
6	S14	G4	0.4794	0.7282	1.2076	0.2488
7	S05	G2	0.5518	0.6495	1.2013	0.0977
8	S15	G4	0.4706	0.7220	1.1926	0.2514
9	S06	G2	0.5435	0.6424	1.1859	0.0988
10	S16	G4	0.4650	0.7179	1.1829	0.2529
11	S07	G2	0.5311	0.6316	1.1627	0.1006
12	S08	G2	0.5231	0.6248	1.1479	0.1017
13	S09	G3	0.3453	0.6292	0.9744	0.2839
14	S10	G3	0.3415	0.6253	0.9668	0.2838
15	S11	G3	0.3358	0.6191	0.9549	0.2833
16	S12	G3	0.3322	0.6151	0.9473	0.2829
17	S17	G5	0.2990	0.5544	0.8534	0.2554
18	S18	G5	0.2947	0.5488	0.8435	0.2541
19	S19	G5	0.2882	0.5400	0.8282	0.2518
20	S20	G5	0.2842	0.5344	0.8186	0.2502
21	S21	G6	0.2317	0.3619	0.5936	0.1302
22	S22	G6	0.2250	0.3550	0.5800	0.1299
23	S23	G6	0.2152	0.3444	0.5596	0.1292
24	S24	G6	0.2090	0.3377	0.5467	0.1287

Table A7. UW-TOPSIS proximity intervals under the cost scenario (case 3).

Rank	Alt.	Group	R^L	R^U	Score	Width
1	S01	G1	0.8440	0.8877	1.7317	0.0438
2	S02	G1	0.8367	0.8820	1.7187	0.0454
3	S03	G1	0.8253	0.8727	1.6980	0.0474
4	S04	G1	0.8180	0.8665	1.6845	0.0485
5	S09	G3	0.4543	0.7708	1.2252	0.3165
6	S10	G3	0.4502	0.7679	1.2181	0.3177
7	S11	G3	0.4438	0.7630	1.2068	0.3192
8	S05	G2	0.5700	0.6358	1.2058	0.0658
9	S12	G3	0.4397	0.7597	1.1994	0.3200
10	S06	G2	0.5615	0.6282	1.1896	0.0667
11	S07	G2	0.5485	0.6165	1.1650	0.0679
12	S08	G2	0.5402	0.6090	1.1492	0.0687
13	S13	G4	0.3700	0.6382	1.0082	0.2682
14	S14	G4	0.3637	0.6335	0.9972	0.2697
15	S15	G4	0.3539	0.6260	0.9799	0.2720
16	S16	G4	0.3477	0.6211	0.9688	0.2734
17	S21	G6	0.2611	0.4136	0.6747	0.1526
18	S22	G6	0.2552	0.4065	0.6617	0.1513
19	S23	G6	0.2464	0.3955	0.6419	0.1491
20	S17	G5	0.1789	0.4532	0.6321	0.2744
21	S24	G6	0.2409	0.3884	0.6294	0.1475
22	S18	G5	0.1755	0.4482	0.6237	0.2726
23	S19	G5	0.1706	0.4402	0.6108	0.2695
24	S20	G5	0.1678	0.4351	0.6029	0.2673

Table A8. UW-TOPSIS proximity intervals under the technical scenario (case 4).

Rank	Alt.	Group	R^L	R^U	Score	Width
1	S01	G1	0.8475	0.8994	1.7469	0.0519
2	S02	G1	0.8403	0.8942	1.7345	0.0538
3	S03	G1	0.8291	0.8855	1.7145	0.0564
4	S04	G1	0.8218	0.8796	1.7014	0.0578
5	S05	G2	0.5791	0.6523	1.2314	0.0732
6	S06	G2	0.5709	0.6447	1.2156	0.0738
7	S07	G2	0.5585	0.6330	1.1915	0.0745
8	S08	G2	0.5506	0.6256	1.1762	0.0749
9	S13	G4	0.4582	0.6914	1.1496	0.2332
10	S14	G4	0.4522	0.6870	1.1392	0.2348
11	S15	G4	0.4429	0.6801	1.1229	0.2372
12	S16	G4	0.4369	0.6755	1.1124	0.2387
13	S09	G3	0.3921	0.6599	1.0519	0.2678
14	S10	G3	0.3880	0.6559	1.0439	0.2678
15	S11	G3	0.3818	0.6495	1.0313	0.2677
16	S12	G3	0.3779	0.6453	1.0232	0.2674
17	S17	G5	0.2642	0.5069	0.7711	0.2427
18	S18	G5	0.2599	0.5014	0.7614	0.2415
19	S19	G5	0.2535	0.4928	0.7463	0.2393
20	S20	G5	0.2496	0.4874	0.7369	0.2378
21	S21	G6	0.2224	0.3673	0.5896	0.1449
22	S22	G6	0.2169	0.3603	0.5771	0.1434
23	S23	G6	0.2087	0.3495	0.5583	0.1408
24	S24	G6	0.2037	0.3427	0.5464	0.1390

References

- European Commission. 2050 Long-Term Strategy. Available online: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en (accessed on 5 May 2024).
- Gallagher, C.; Stuart, C.; Spence, S. Liquid Hydrogen and Synthetic Sustainable Aviation Fuel: A European Airline Case Study. In Proceedings of the GPPS Chania24, Crete, Greece, 4–6 September 2024. [CrossRef]
- Vogiantzi, C.; Tserpes, K. On the Definition, Assessment, and Enhancement of Circular Economy across Various Industrial Sectors: A Literature Review and Recent Findings. *Sustainability* **2023**, *15*, 16532. [CrossRef]
- Whittle, J.W.; Callander, K.; Akure, M.; Kachwala, F.; Koh, S.C.L. A New High-Level Life Cycle Assessment Framework for Evaluating Environmental Performance: An Aviation Case Study. *J. Clean. Prod.* **2024**, *471*, 143440. [CrossRef]
- Kurzawska-Pietrowicz, P. Life Cycle Emission of Selected Sustainable Aviation Fuels—A Review. *Transp. Res. Procedia* **2023**, *75*, 77–85. [CrossRef]
- Pinto, D.B.S.B. Hydrogen Aircraft Conceptual Design and Life Cycle Assessment. Master's Thesis, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal, 2022.
- Boddorff, A.K. *Choosing the Right Stuff: Material Selection for Liquid Hydrogen Aircraft Cryotanks*; NASA Technical Memorandum NASA/TM-20250007133; National Aeronautics and Space Administration, Langley Research Center: Hampton, VA, USA, 2025. Available online: <https://ntrs.nasa.gov/citations/20250007133> (accessed on 1 March 2026).
- Pantelakis, S.; Tserpes, K. (Eds.) *Revolutionizing Aircraft Materials and Processes*; Springer International Publishing: Cham, Switzerland, 2020. [CrossRef]
- Benitez, A.; Wulf, C.; de Palmenaer, A.; Lengersdorf, M.; Röding, T.; Grube, T.; Robinius, M.; Stolten, D.; Kuckshinrichs, W. Ecological Assessment of Fuel Cell Electric Vehicles with Special Focus on Type IV Carbon Fiber Hydrogen Tank. *J. Clean. Prod.* **2021**, *278*, 123277. [CrossRef]
- Ye, L.; Lu, L. Environmental and Economic Evaluation of the High-Pressured and Cryogenic Vessels for Hydrogen Storage on the Sedan. *Int. J. Low-Carbon Technol.* **2023**, *18*, 144–149. [CrossRef]
- Ren, J. (Ed.) *Energy Systems Evaluation (Volume 2): Multi-Criteria Decision Analysis*; Green Energy and Technology; Springer: Cham, Switzerland, 2021. [CrossRef]

12. Anagnostopoulou, A.; Sotiropoulos, D.; Tserpes, K. A Robust Sustainability Assessment Methodology for Aircraft Parts: Application to a Fuselage Panel. *Sustainability* **2025**, *17*, 3299. [[CrossRef](#)]
13. Anagnostopoulou, A.; Sotiropoulos, D.; Sioutis, I.; Tserpes, K. Sustainability-Driven Design Optimization of Aircraft Parts Using Mathematical Modelling. *Aerospace* **2026**, *13*, 95. [[CrossRef](#)]
14. Liern, V.; Pérez-Gladish, B. Multiple Criteria Ranking Method Based on Functional Proximity Index: Un-weighted TOPSIS. *Ann. Oper. Res.* **2022**, *311*, 1109–1137. [[CrossRef](#)]
15. Liern, V.; Pérez-Gladish, B. Building Composite Indicators with Unweighted-TOPSIS. *IEEE Trans. Eng. Manag.* **2023**, *70*, 1871–1880. [[CrossRef](#)]
16. ISO 14040:2006; Environmental Management—Life Cycle Assessment—Principles and Framework. ISO: Geneva, Switzerland, 2006.
17. ISO 14044:2006; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. ISO: Geneva, Switzerland, 2006.
18. Cañós, L.; Liern, V. Soft Computing-Based Aggregation Methods for Human Resource Management. *Eur. J. Oper. Res.* **2008**, *189*, 669–681. [[CrossRef](#)]
19. Hwang, C.-L.; Yoon, K. *Multiple Attribute Decision Making*; Lecture Notes in Economics and Mathematical Systems; Springer: Berlin, Germany, 1981; Volume 186.
20. Diakoulaki, D.; Mavrotas, G.; Papayannakis, L. Determining Objective Weights in Multiple Criteria Problems: The CRITIC Method. *Comput. Oper. Res.* **1995**, *22*, 763–770. [[CrossRef](#)]
21. Zelený, M. *Multiple Criteria Decision Making*; McGraw-Hill: New York, NY, USA, 1982.
22. Wang, Y.-M.; Luo, Y. Integration of Correlations with Standard Deviations for Determining Attribute Weights in Multiple Attribute Decision Making. *Math. Comput. Model.* **2010**, *51*, 1–12. [[CrossRef](#)]
23. Keshavarz-Ghorabae, M.; Amiri, M.; Zavadskas, E.K.; Turskis, Z.; Antucheviciene, J. Determination of Objective Weights Using a New Method Based on the Removal Effects of Criteria (MEREC). *Symmetry* **2021**, *13*, 525. [[CrossRef](#)]
24. Keshavarz-Ghorabae, M. Assessment of Distribution Center Locations Using a Multi-Expert Subjective–Objective Decision-Making Approach. *Sci. Rep.* **2021**, *11*, 19461. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.