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Sustainable stationary hydrogen storage application selection with interval-valued intuitionistic fuzzy AHP

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ABSTRACT

The transition to a hydrogen-based economy necessitates a comprehensive evaluation of different hydrogen storage options, considering their sustainability performance. This study innovatively applies the Interval-Valued Intuitionistic Fuzzy Analytic Hierarchy Process (IVIF-AHP) to evaluate and compare four hydrogen storage options: Compressed Hydrogen Gas (CHG), Cryogenic Liquid Hydrogen (CLH), Metal Hydride (MH), and Underground Hydrogen (UH). The evaluation criteria are derived from four dimensions of sustainability: economic, environmental, social, and technical performance, each further decomposed into sub-criteria. The study's novelty lies in using a novel intuitionistic fuzzy AHP, offering a more nuanced and robust understanding of the trade-offs between the various options and effectively capturing the vagueness and subjectivity inherent in human decision-making. Through this methodology, CHG emerged as the most promising option with a preference score of 0.487, closely followed by UH with a score of 0.453. The lowest preference score was accorded to MH, with a score of 0.301. These quantitative insights underscore the relative sustainability performance of each technology under the defined criteria. The findings contribute to the growing body of literature on sustainable hydrogen storage, providing policymakers and practitioners with a multicriteria decision-making tool that captures the complexity of sustainability considerations. This study underlines the critical role of holistic, multicriteria evaluations in advancing sustainable hydrogen storage. It encourages further exploration and validation of its approach in different contexts and with updated technological advancements.

1. Introduction

The global energy landscape is experiencing a significant transformation towards low-carbon systems, necessitated by the urgent need to mitigate the effects of climate change. This transition requires increasing the use of intermittent renewable energy sources such as solar and wind power. Consequently, the need for effective energy storage mechanisms has become increasingly important [1], with hydrogen emerging as a promising energy carrier and storage medium across various sectors, including transportation, power generation, and industry [2].

Hydrogen storage poses distinct challenges regarding safety, efficiency, and sustainability. A variety of stationary hydrogen storage methods exist, such as Compressed Hydrogen Gas (CHG), Cryogenic Liquid Hydrogen (CLH), Metal Hydride (MH), and Underground Hydrogen (UH), each presenting a unique set of advantages and disadvantages [3]. Evaluating these methods from a sustainability perspective necessitates the consideration of a broad array of criteria, encompassing economic, environmental, social, and technical aspects [4].

The existing literature on this topic primarily targets technical aspects, often sidelining a comprehensive sustainability evaluation incorporating multiple dimensions. A more holistic evaluation of hydrogen storage options, capable of informing stakeholders, is currently absent from the scholarly discourse. It is this gap that the present study aims to address.

Through the application of a multicriteria decision-making analysis, our research undertakes a comprehensive evaluation of the sustainability performance of CHG, CLH, MH, and UH, considering criteria such as capital cost, operating cost, levelized cost of hydrogen, GHG emissions, land use requirements, water consumption, solid waste generation, safety, accessibility, ease of use, public acceptance, efficiency, energy density, power density, and cycle life.

In a novel approach, our study employs an interval-valued intuitionistic fuzzy Analytic Hierarchy Process (IVIF-AHP) to compare these

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storage options. This method allows us to capture the inherent subjectivity and ambiguity in human decision-making, providing a more nuanced understanding of the trade-offs involved.

It is important to note that while our study offers a comparative analysis of selected hydrogen storage options, it does not purport to cover all aspects of hydrogen storage or all potential storage methods. Instead, it aims to provide a reliable and comprehensive decision-making tool that aids in selecting the most sustainable hydrogen storage methods for stationary applications.

This study makes a significant contribution to the literature, being, to the best of our knowledge, the first to apply IVIF-AHP in assessing the sustainability of hydrogen storage options. Moreover, it promises to deliver practical value for policymakers, practitioners, and researchers in the hydrogen energy sector, assisting in aligning hydrogen storage options with specific sustainability goals and contexts. By facilitating a comprehensive, robust, and context-specific sustainability evaluation, this study stands to play a vital role in shaping future energy systems that are both sustainable and resilient.

2. Literature review

This section aims to reveal the methodological gaps in the MCDM literature handling hydrogen storage-related problems. Because the evaluation of hydrogen storage in different dimensions has a conflicting structure, including quantitative and qualitative criteria, MCDM has been widely used in this area, mainly in the following issues: (1) site selection, (2) risk evaluation, (3) project selection, (4) method selection (production, storage, etc., selection), and (5) performance assessment. These studies are summarized below regarding which methods were utilized, which criteria were considered, and which issues were being practiced.

2.1. Site selection

In the study of Kokkinos et al. [5], a comparative study for selecting the best hydrogen storage location scenario was improved in which triangular intuitionistic fuzzy sets showed qualitative criteria. Three alternative scenarios were overseen ((1) nearby Steiner points, (2) maximization of safety, (3) nearby operators), and three criteria groups were considered: hydrogen infrastructure, socioeconomics, and fleet and road network, with their fifteen sub-criteria. For the MCDM method, FWASPAS, IFCOPRAS, IFEDAS, and IFCODAS were applied, and at each calculation, the rank of alternative scenarios was found to be the same (1, 3, and 2). Gao et al. [6] introduced an extended TODIM (TOmada de Decisao Iterativa Multicriterio) procedure to select the most appropriate location for the photovoltaic power coupling hydrogen storage. They conducted a comparative study to show how MCDM methods differ in the results. Economy, environmental, social, and risk criteria were chosen as the main criteria, and they had sixteen sub-criteria. The comparative study shows that the extended TODIM gives different results than conventional MCDM methods (such as PROMETHEE and VIKOR) because it considers decision-makers' awareness of risk aversion. Wu et al. [7] proposed a hybrid MCDM model to select the best site for wind power-coupled hydrogen storage projects. In the model, four main criteria named resource, economy, environment, and society were taken into consideration. Firstly, qualitative criteria were identified by utilizing triangular intuitionistic fuzzy numbers, and then the criteria were prioritized by using the fuzzy entropy model. The fuzzy TODIM (TOmada de Decisão Iterativa Multicritério) method was used to find the best site. Iordache et al. [8] proposed a hybrid method, including Additive Ratio Assessment (ARAS) method and interval type-2 hesitant fuzzy sets (IT2HFSs) for the underground hydrogen storage site selection problem. Four site options were evaluated regarding seven main and fourteen sub-criteria. The seven main criteria are geographic aspects, geological aspects, industrial infrastructure, electric network infrastructure, fleet, R&D, and risk. In the study of Narayanamoorthy et al. [9], a normal wiggly dual hesitant fuzzy set-based VIKOR (VIseKriterijumsa Optimizacija I Kompromisno Resenje) methodology was utilized to select the best site for underground hydrogen storage. The methodology considered five main criteria named: technique of operation, investment cost, social, economic, and risk. The selection procedure was performed to select the best among the three alternatives. Deveci [10] oversaw the problem of selecting hydrogen underground storage sites utilizing an interval type-2 hesitant fuzzy set-based MCDM method. The methodology considered four main criteria, including technique characteristics, costs, socioeconomic characteristics, and risks, with fourteen sub-criteria. As a result, investment cost was found to be the most effective sub-criterion on the site selection. Lewandowska-Smierzchalska et al. [11] developed an AHP-based methodology for site selection considering six main criteria (reservoir lithology, stage of exploration, type of salt deposit, reservoir volume, depth, and geothermal gradient). Salt caverns, deep aquifers, and depleted hydrocarbon deposits were selected as the alternative sites for hydrogen underground storage.

2.2. Risk evaluation

Sun et al. [12] developed a multi-phase MCDM procedure to evaluate the risk of storage and transportation of hydrogen. To weigh the key factors (people-related risk, storage risk, transportation risk, environmental risk, and management risk), DEMATEL-ANP (decision-making trial and evaluation laboratory with the analytic network process) was applied, and then the levels of the risks were calculated with fuzzy evaluation. As a result, it was revealed that the personnel's skills, environmental volatility, and effectiveness of feedback have a high importance on the risk. In the study of Uliasz-Misiak et al. [13], an AHP-based methodology was proposed to select the best risk evaluation method associated with underground hydrogen storage. They consider six criteria: the type of the method, the frequency of the method, the type of data, the effort to apply, including a probability analysis in the method, and a consequence analysis in the method. Among seven alternative techniques (Monte Carlo Simulation, Hazard, and Operability Studies (HAZOP), Bow-Tie Analysis, Fault Tree Analysis (FTA), Delphi Analysis, reliability-centered maintenance (RCM), and consistency indices), RCM was found to be the best technique for risk evaluation. Wu et al. [14] offered an assessment process for the risk of wind-photovoltaic-hydrogen storage projects. In the methodology, there are two steps: (1) weighting the criteria with the help of the analytic hierarchy process (AHP) and (2) calculating the overall risk of the projects by utilizing fuzzy synthetic evaluation. They listed four main risk criteria (economic, technical, environmental, and safety) and fourteen sub-criteria. Environmental risks have been found to be the most important one. Nevertheless, in the case of China, the overall risk is technological. Besides that, the risk of the project is between low and medium. Yi and Li [15] proposed a linguistic hesitant fuzzy sets (LHFSs) based methodology for the application risk assessment of gaseous hydrogen storage alternatives in a sustainable manner. They identified four main risk criteria (technical, economic environment, natural environment, social and political environment) with their total eleven sub-criteria. The proposed model was applied to China, and gaseous hydrogen storage density, fiscal subsidy policy, government regulation, and public acceptance were revealed as the highest risk criteria.

2.3. Project selection

In the study of Guo et al. [16], a decision procedure for offshore wind power photovoltaic hydrogen storage project was developed regarding four main criteria (economy, resources, environment, and supporting conditions) and their sixteen sub-criteria. The maximizing deviation method with the probabilistic linguistic-DEMATEL was utilized to identify the criteria weights, and the ranks of the alternatives were revealed by using an improved PROMETHEE method. Wu et al. [17] proposed a five-phase fuzzy MCDM method including four main criteria (resource, economy, environmental, and social) and twelve sub-criteria for selecting the best investment for a photovoltaic power coupling hydrogen storage project. To sort the projects, triangular intuitionistic fuzzy TODIM was used.

2.4. Method selection

In the study of İlbahar et al. [18], an integrated methodology was utilized to find the best hydrogen energy storage option. In the methodology, firstly, Z-fuzzy DEMATEL was applied to reveal the dependencies between criteria. Technical conditions, economic perspective, environmental effects, and social aspects were considered as the main criteria. Secondly, six alternatives (compressed gas, cold/-cryo compression, liquid H_2, carbon nanotubes, metal hydrides, and chemical hydrogen) were evaluated by utilizing Z-fuzzy VIKOR. Carbon nanotubes were found to be the most appropriate hydrogen energy storage option. Karatas [19] proposed a hybrid MCDM method for hydrogen energy storage selection, including fuzzy AHP and Weighted Fuzzy Axiomatic Design. Weight, capacity, storage loss and leak, reliability, and total system cost were defined as the main criteria of the proposed method. The selection procedure was performed among alternatives: tank, metal hydride, and chemical storage. The metal hydride option was found to be more successful regarding many criteria. Acar et al. [20] proposed a Hesitant Fuzzy AHP-based MCDM methodology to select the best sustainable hydrogen production option. The alternatives were determined as grid electrolysis, wind electrolysis, PV electrolysis, nuclear thermochemical water splitting cycles, solar thermochemical water splitting cycles, and photoelectrochemical cells. Economic performance, environmental performance, social performance, technical performance, and availability/reliability were selected as the main criteria affecting the selection. As a result, it was found that grid electrolysis was the most appropriate option for sustainable hydrogen production. Montignac et al. [21] used the MACBETH methodology to decide on the best hydrogen storage systems for future vehicles. In the methodology, five technical criteria were considered: system volume, system mass, refueling time, hydrogen loss rate, and conformability, and three alternative technologies (pressure, liquid, and solid) were evaluated. In the study of Gim and Kim [22], an AHP-based MCDM methodology was followed to assess hydrogen storage systems for automobiles. Weight efficiency, volume efficiency, system cost, energy efficiency, cycle life, refueling time, safety, and infrastructure were selected as criteria affecting the evaluation process. Among the alternatives (350 bar compressed gas hydrogen (CH2 350), 700 bar compressed gas hydrogen (CH2 700), liquefied hydrogen (LH2), metal hydride (MH), and chemical hydride (CH)), compressed gas hydrogen was found as the most appropriate system. Gumus et al. [23] utilized an integrated model to select the best hydrogen energy storage method among three alternatives (tank, metal hydride, and chemical storage). Fuzzy AHP was used to weigh the criteria (weightlessness, capacity, storage loss and leak, reliability, and total system cost), and linear normalization-based fuzzy Grey Relational Analysis (Fuzzy-GRA) was used to rank the alternatives.

2.5. Performance assessment

Wu et al. [24] developed a sustainable methodology for evaluating the performance of wind power coupling hydrogen storage projects. They considered three dimensions of sustainability: economic, environmental, and social. To weigh the criteria, the interval type-2 fuzzy Analytic Hierarchy Process (AHP) was applied, and then, the interval type-2 fuzzy Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) was applied to rank the alternatives.

The above studies provide methodologies for solving the problems of hydrogen storage with the help of MCDM methods. Although they aim to oversee the problems from different dimensions, it is still highly significant to deal with the ambiguity of the expressions of the experts by utilizing a novel MCDM method. Therefore, in this study, interval-valued intuitionistic fuzzy sets (IVIFSs) are utilized to endow decision-makers with the capability of expressing both optimistic and pessimistic evaluations of each decision, thereby facilitating their decision-making process. This approach allows for greater flexibility in decision-making and can lead to more robust and effective decision outcomes.

The IVIF-AHP is a novel decision-making approach that has not previously been applied to comparing hydrogen storage methods. This method allows us to deal with the inherent uncertainties and vagueness involved in the decision-making process, making it highly suitable for this type of multicriteria analysis. The methodology also facilitates the expression of the experts' judgments more flexibly compared to classical AHP. Therefore, the use of IVIF-AHP in this study not only presents a novel approach in the context of hydrogen storage methods but also adds to the existing literature by showcasing the applicability of this methodology to complex decision-making scenarios in sustainable energy.

3. Sustainability performance criteria

In assessing sustainable stationary hydrogen storage options, we consider a holistic framework that integrates economic, environmental, social, and technical aspects (Fig. 1). Each criterion is decomposed into multiple sub-criteria to capture the multifaceted nature of sustainable performance.

Each of these specific sub-criteria under four main overarching sustainability criteria comprehensively appraises the different hydrogen storage technologies. Here is an in-depth discussion of each criterion and its sub-components.

3.1. Economic performance

The economic performance of hydrogen storage technologies is a critical aspect, directly impacting the financial feasibility and competitive edge of these solutions. Three significant factors determine the economic viability:

- **Capital Cost**: This component refers to the total cost needed to establish and install the hydrogen storage system, including expenses for construction, equipment, and setup. It captures the initial investment required to set up the storage system. Lower capital costs can make a hydrogen storage option more appealing to investors and speed up its adoption.
- **Operating Cost**: Operating cost reflects the ongoing expenses associated with running the hydrogen storage facility, including maintenance, repair, replacement, energy consumption, and human resources.
- **Levelized Cost of Hydrogen**: This metric expresses the average cost of storing hydrogen over the lifetime of a storage system. It provides an overall measure of the long-term economic efficiency of the selected hydrogen storage technologies.

3.2. Environmental performance

The environmental performance of a hydrogen storage system evaluates its impact on the climate and environment, including ecosystems and all habitants:

- **Greenhouse Gas (GHG) Emissions**: This metric refers to the total quantity of greenhouse gases emitted during the lifecycle of the hydrogen storage system, including during manufacturing, operation, and decommissioning.
- **Land Use Requirements**: This metric measures the physical space needed to install and operate the hydrogen storage system. Lower

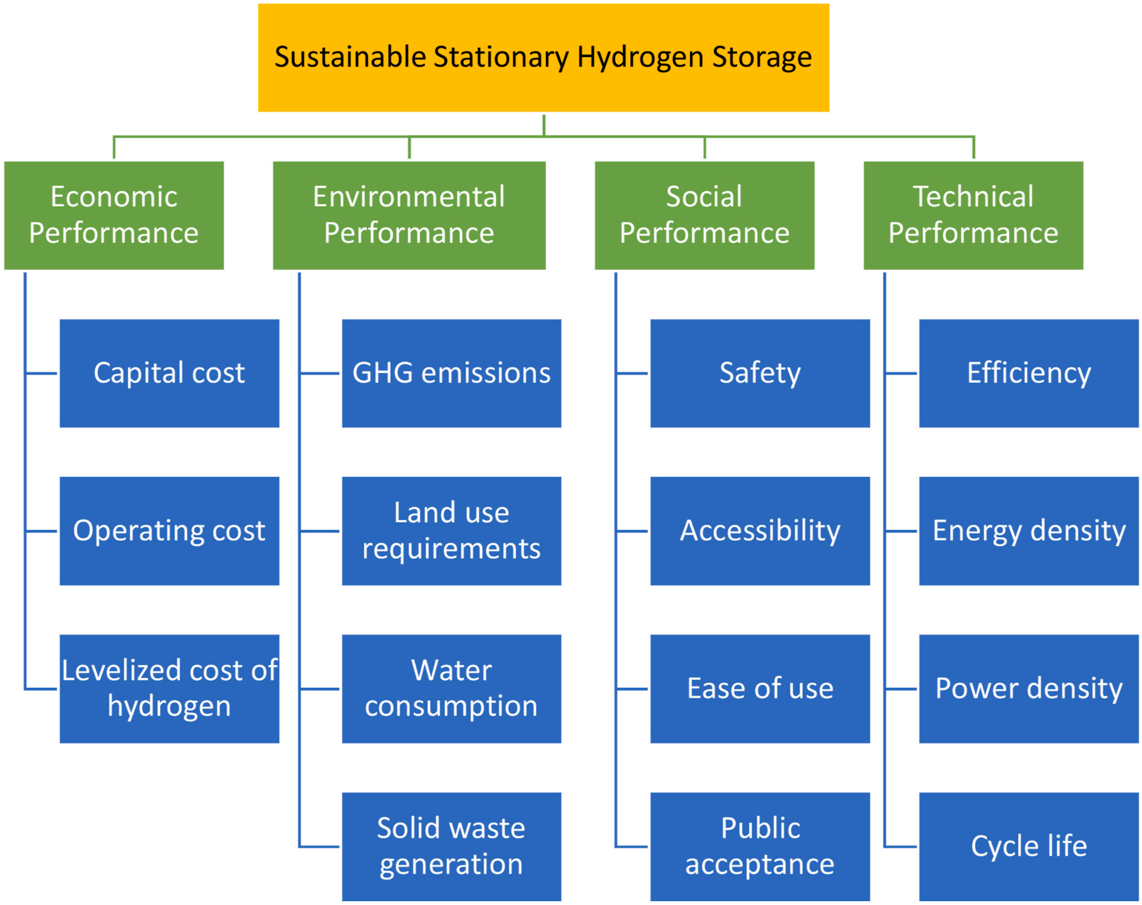

Fig. 1. Sustainable stationary hydrogen storage criteria.

land use requirements can reduce the environmental footprint and potential habitat disruption.

- **Water Consumption**: This criterion quantifies the amount of water needed in the lifecycle of the hydrogen storage system, including production, operation, and decommissioning. Considering water scarcity and the associated environmental implications, this criterion can significantly impact decision-making.
- **Solid Waste Generation**: This metric evaluates the amount of solid waste produced during the lifecycle of the hydrogen storage system. This waste can impact soil and water quality if not responsibly managed.

3.3. Social performance

The social performance criterion evaluates the societal implications of hydrogen storage systems:

- **Safety**: This sub-criterion evaluates potential risks and hazards associated with the operation and management of the hydrogen storage system, considering both workers and local communities. Some of the safety concerns are leaks, explosions, and fires.
- **Accessibility**: This metric examines the ease of access to the technology. It evaluates how easily the system can be deployed and accessed, considering aspects like geographic location, infrastructure availability, resource requirements, and logistical constraints.
- **Ease of Use**: This refers to the user-friendliness and simplicity of managing and operating the hydrogen storage system.
- **Public Acceptance**: This assesses the public perception and acceptance of the technology, which can significantly impact the adoption and successful implementation of the hydrogen storage solution.

3.4. Technical performance

Technical performance is critical to determining the functionality and effectiveness of hydrogen storage technologies:

- **Efficiency**: This metric refers to the energy conversion efficiency of the hydrogen storage system or how much of the input energy is stored and then retrievable. It assesses the ability of the system to store and release hydrogen with minimal losses.
- **Energy Density**: This criterion assesses the amount of energy that can be stored in a given volume or mass of the storage medium.
- **Power Density**: This criterion refers to the system's capacity to deliver high power output in a given volume or mass of the storage medium. It also influences the storage system's responsiveness to demand fluctuations.
- **Cycle Life**: This metric measures the number of complete charge-discharge cycles the storage system can perform before its performance degrades to a certain level. It also reflects the storage system's durability and longevity.

In sum, the decision-making process for sustainable stationary hydrogen storage applications requires an intricate balance among these multifaceted performance criteria. By decomposing each criterion into specific, measurable components, the selection process becomes more transparent, comprehensive, and robust, facilitating the development and implementation of genuinely sustainable hydrogen storage solutions.

4. Hydrogen storage options

In the context of sustainable energy solutions, hydrogen storage plays a significant role in decarbonizing various sectors. The following section presents a detailed overview of four key hydrogen storage options under consideration in this study: compressed hydrogen gas, cryogenic liquid hydrogen, metal hydrides, and underground hydrogen storage.

4.1. Compressed hydrogen gas (CHG)

Compressed hydrogen gas storage is the most common method of storing hydrogen today. In this method, hydrogen gas is stored under high pressure (typically 350–700 bar) in specially designed tanks [25]. The process allows for considerable storage volume while maintaining a relatively simple design. Despite this, the energy required to compress the gas and the cost of the robust tanks needed to withstand high pressure are among the primary challenges [26].

Advancements in materials, like carbon composites, have enabled lighter and safer tanks. However, the energy efficiency of the compression process and the space requirements for storage remain concerns [27]. Compressed gas storage is most suitable for applications that require moderate storage volume and short-term storage durations, such as in transportation or grid-balancing operations [28].

4.2. Cryogenic liquid hydrogen (CLH)

Liquid hydrogen storage is another viable method involving the cooling and liquefaction of hydrogen gas to temperatures below its boiling point (around −253 °C). The primary advantage of liquid hydrogen storage is the high energy density it achieves, about three times higher than gasoline [29].

However, the liquefaction process is energy-intensive, consuming about 30–40% of the energy content of the hydrogen [30]. Additionally, storage tanks must be well-insulated to prevent heat leakage and consequential hydrogen evaporation, known as 'boil-off.' This method is typically employed for short-term storage or for applications that require high energy density, like aerospace and heavy transport [31].

4.3. Metal hydrides (MH)

Metal hydrides offer an attractive alternative for hydrogen storage, especially for stationary applications. Hydrogen atoms are stored in the atomic structure of certain metals or alloys, forming metal hydrides [32]. These systems are typically compact, safe, and offer high volumetric energy density, making them suitable for residential or commercial energy storage [33].

Despite these benefits, metal hydrides face challenges, including the often-high cost of suitable hydride materials, slower hydrogen absorption and desorption rates, and heat management issues during the loading and unloading processes [34]. Research is ongoing to overcome these hurdles and optimize the technology for broader applications.

4.4. Underground hydrogen (UH)

Underground hydrogen storage utilizes geological formations, such as depleted gas reservoirs, salt caverns, or aquifers, to store large volumes of hydrogen gas [35]. This method can offer vast storage capacities and long storage durations, potentially seasonal, making it well-suited for grid-scale energy storage applications [36].

Challenges include ensuring the hydrogen's purity and containment and assessing the site's suitability and safety. Also, this method requires substantial infrastructure for hydrogen injection, withdrawal, and conditioning. While underground hydrogen storage is promising for large-scale renewable energy integration, more research and demonstration projects are needed to establish its commercial viability [37].

In conclusion, the diverse hydrogen storage options offer unique advantages and face distinct challenges, each suited to specific applications based on their technical, economic, environmental, and social performance criteria. Compressed hydrogen gas storage and cryogenic liquid hydrogen storage are well-established methods with high capacity, while metal hydrides and underground storage present compelling alternatives for specialized applications. The choice of the optimal storage solution must consider the requirements of the intended application, the technology's readiness level, and the location-specific factors such as infrastructure and geology. As research and development efforts continue to refine these technologies, it is anticipated that the efficiency, cost-effectiveness, and sustainability of hydrogen storage will significantly improve, making hydrogen a viable and critical player in the global sustainable energy landscape. The challenge and opportunity for researchers, policymakers, and industry practitioners alike are to collaboratively address these issues and unlock the full potential of hydrogen storage for a sustainable energy future.

5. Methodology

MCDM comprises a diverse set of tools designed to assist managers in making complex decisions that involve the simultaneous consideration of multiple qualitative and quantitative criteria. These criteria often exhibit inherent conflicts. Expert opinions are considered to determine the relative weights of the criteria and evaluate alternatives.

In the application of the AHP, a substantial number of participants is not obligatory to yield valid findings. As posited by Ref. [38], the involvement of even a single qualified expert possessing profound domain knowledge and practical expertise relevant to the subject of investigation, can yield outcomes that are both representative and robust. The inclusion of additional experts has the potential to adversely affect the precision and consistency of the assessment [38,39]. Hence, careful consideration should be given to the expertise and qualifications of participants to ensure the integrity of the assessment process.

In this study, the multicriteria decision-making process relies on the opinions of three distinguished experts in hydrogen storage. The first expert is a seasoned researcher affiliated with the International Association for Hydrogen Energy, boasting over a decade of experience specifically focused on hydrogen storage research. The second expert is a renowned scientist and active member of Hydrogen Europe, contributing significantly to the advancement of hydrogen technologies. The final expert is a professional member of the Dutch Hydrogen Association, bringing a wealth of practical experience and a unique perspective on hydrogen applications. Each expert was selected based on their extensive knowledge, experience, and contributions to hydrogen storage research and development, ensuring the reliability and validity of their opinions in shaping our analysis. This range of expertise strengthens our evaluation process, bringing a broad yet nuanced perspective to the decision-making process.

Some well-known and widely used MCDM tools include Analytic Hierarchy Process (AHP) [40–44], ELimination Et Choix Traduisant la REalité (ELimination and Choice Expressing Reality – ELECTRE) [45,46], preference ranking organization method for enrichment evaluation (PROMETHEE) [47,48], and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [49,50]. Among these tools, AHP has gained significant popularity [51,52] due to its comprehensive ability to manage the entire decision-making process, ranging from defining criteria weights to selecting the most favorable alternative.

To address the issue of inadequate data and ambiguity encountered in many real-world scenarios, fuzzy sets have emerged as a widely adopted approach in conjunction with MCDM methods. As the challenges of inadequacy and vagueness have escalated in modern business environments, various extensions have been introduced to the fuzzy-set family, including type-II, intuitionistic, hesitant, Pythagorean, picture, neutrosophic, and spherical fuzzy sets.

Decisions on sustainable stationary hydrogen storage application selection inherently involve ambiguity and complexity due to the need to address conflicting criteria using both qualitative and quantitative data simultaneously. Consequently, the interval-valued intuitionistic fuzzy Analytic Hierarchy Process (IVIF-AHP) aligns exceptionally well with the nature of such problems and offers a fitting solution. IVIF-AHP is particularly useful when dealing with uncertain or imprecise information. Traditional AHP requires precise numerical values for comparisons, while IVIF-AHP allows decision-makers to express their judgments in the form of interval-valued intuitionistic fuzzy numbers, accommodating uncertainty in the decision-making process. It provides a rich representation for decision-makers to express their preferences. It allows for the modeling of not only membership degrees but also non-membership degrees and hesitation degrees, which capture the degree of uncertainty and vagueness in their judgments and enhances the robustness of the decision-making process leading to more realistic and reliable results. The use of interval-valued intuitionistic fuzzy numbers allows for the representation of the best and worst-case scenarios, which is valuable in management. Afterall, the method provides a structured framework for decision-making, making it transparent and easier for stakeholders to understand how the final decision was reached. In many industrial practices, IVIF-AHP method has been utilized such as [53–59]. In the following sections, preliminaries of IVIF sets and the IVIF-AHP method are presented.

5.1. Interval-valued intuitionistic fuzzy sets

An interval-valued intuitionistic fuzzy number (IVIFN), $\widetilde{A}$, can be defined in the universe of discourse X as in Eq. (1).

$$\widetilde{A} = \{ < x, [\mu_{\widetilde{A}}^L(x), \mu_{\widetilde{A}}^U(x)], [v_{\widetilde{A}}^L(x), v_{\widetilde{A}}^U(x)] > |x \in X\} \tag{1}$$

where $\mu_{\widetilde{A}}^L(x) : X \rightarrow [0,1]$ and $\mu_{\widetilde{A}}^U(x) : X \rightarrow [0,1]$ are the lower and upper degrees of membership, respectively, and $v_{\widetilde{A}}^L(x) : X \rightarrow [0,1]$ and $v_{\widetilde{A}}^U(x) : X \rightarrow [0,1]$ are the lower and upper degrees of non-membership of x, respectively satisfying, $0 \leq \mu_{\widetilde{A}}^U(x) + v_{\widetilde{A}}^U(x) \leq 1$ and $\mu_{\widetilde{A}}^L(x) \geq 0, v_{\widetilde{A}}^L(x) \geq 0$.

Considering IVIFNs such as $\widetilde{A} = ([\mu_{\widetilde{A}}^L, \mu_{\widetilde{A}}^U], [v_{\widetilde{A}}^L, v_{\widetilde{A}}^U])$, basic operations used in this study are given in Eqs. (2)–(4) [60].

- **The Interval-Valued Intuitionistic Fuzzy Weighted Arithmetic Mean (IVIFWAM)** of n IVIFNs ($\widetilde{A}_i = ([\mu_{\widetilde{A}_i}^L, \mu_{\widetilde{A}_i}^U], [v_{\widetilde{A}_i}^L, v_{\widetilde{A}_i}^U])$), given the weight vector $(\lambda_1, \lambda_2, \ldots, \lambda_n)$ where $\lambda_i \in [0,1]$ and $\sum_{i=1}^n \lambda_i = 1$:

$$IVIFWAM(\widetilde{A}_1, \widetilde{A}_2, \ldots, \widetilde{A}_n) = \lambda_1 \cdot \widetilde{A}_1 \oplus \lambda_2 \cdot \widetilde{A}_2 \oplus \ldots \oplus \lambda_n \cdot \widetilde{A}_n$$
$$= \left\{ \left[1 - \prod_{i=1}^n \left(1 - \mu_{\widetilde{A}_i}^L\right)^{\lambda_i}, 1 - \prod_{i=1}^n \left(1 - \mu_{\widetilde{A}_i}^U\right)^{\lambda_i} \right], \left[\prod_{i=1}^n \left(v_{\widetilde{A}_i}^L\right)^{\lambda_i}, \prod_{i=1}^n \left(v_{\widetilde{A}_i}^U\right)^{\lambda_i} \right] \right\} \tag{2}$$

- **The Interval-Valued Intuitionistic Fuzzy Weighted Geometric Mean (IVIFWGM)** of n IVIFNs ($\widetilde{A}_i = ([\mu_{\widetilde{A}_i}^L, \mu_{\widetilde{A}_i}^U], [v_{\widetilde{A}_i}^L, v_{\widetilde{A}_i}^U])$), given the weight vector $(\lambda_1, \lambda_2, \ldots, \lambda_n)$ where $\lambda_i \in [0,1]$ and $\sum_{i=1}^n \lambda_i = 1$:

$$IVIFWGM(\widetilde{A}_1, \widetilde{A}_2, \ldots, \widetilde{A}_n) = \widetilde{A}_1^{\lambda_1} \otimes \widetilde{A}_2^{\lambda_2} \otimes \ldots \otimes \widetilde{A}_n^{\lambda_n}$$
$$= \left\{ \left[\prod_{i=1}^n \left(\mu_{\widetilde{A}_i}^L\right)^{\lambda_i}, \prod_{i=1}^n \left(\mu_{\widetilde{A}_i}^U\right)^{\lambda_i} \right], \left[1 - \prod_{i=1}^n \left(1 - v_{\widetilde{A}_i}^L\right)^{\lambda_i}, 1 - \prod_{i=1}^n \left(1 - v_{\widetilde{A}_i}^U\right)^{\lambda_i} \right] \right\} \tag{3}$$

- An IVIFN ($\widetilde{A}$) is defuzzified by Eq. (4) [61].

$$Deff(\widetilde{A}) = \frac{\mu_{\widetilde{A}}^L + \mu_{\widetilde{A}}^U + (1 - v_{\widetilde{A}}^L) + (1 - v_{\widetilde{A}}^U) + \mu_{\widetilde{A}}^L \mu_{\widetilde{A}}^U - \sqrt{(1 - v_{\widetilde{A}}^L)(1 - v_{\widetilde{A}}^U)}}{4} \tag{4}$$

5.2. Interval-valued intuitionistic fuzzy AHP

Step 1. A hierarchical model of criteria and sub-criteria of the decision problem and the alternatives to be evaluated is prepared primarily through expert consultations.

Step 2. Selected experts compare criteria, sub-criteria, and alternatives in the model by means of pairwise comparisons utilizing linguistic expressions presented in Table 1. In contrast to the classical fuzzy AHP, this approach requires decision-makers to specify a couple of linguistic terms (i.e., optimistic and pessimistic) to articulate their preferences fully.

Step 3. $\widetilde{A}_{ij}^k$ values above the diagonal of the individual pairwise comparison matrix of expert k, are taken from Table 1 to construct $\widetilde{A}'^k$ as in Eq. (5) where $\widetilde{A}_{ij}^k$ is denoted by:

$\widetilde{A}_{ij}^k = ([\mu_{\widetilde{A}_{ij}^k}^L, \mu_{\widetilde{A}_{ij}^k}^U], [v_{\widetilde{A}_{ij}^k}^L, v_{\widetilde{A}_{ij}^k}^U])$ and its reciprocal value, $\widetilde{A}_{ji}^k$, can be found as follows:

$$\widetilde{A}_{ji}^k = \left(\left[v_{\widetilde{A}_{ij}^k}^L, v_{\widetilde{A}_{ij}^k}^U \right], \left[\mu_{\widetilde{A}_{ij}^k}^L, \mu_{\widetilde{A}_{ij}^k}^U \right] \right)$$

$$\widetilde{A}'^k = \begin{bmatrix} (0.4, 0.6), (0.3, 0.4) & \cdots & \widetilde{A}_{1n}^k \\ \vdots & \ddots & \vdots \\ \widetilde{A}_{n1}^k & \cdots & (0.4, 0.6), (0.3, 0.4) \end{bmatrix} \tag{5}$$

Step 4 According to Ref. [62] the formation of aggregate decision matrices should be proceeded only if there is consistency in individual preferences.

To determine the level of consistency in the fuzzy comparison matrices, it is widely recommended to proceed with the consistency of their conjugate crisp versions [63,64].

Since both Saaty's scale and the scale that is used in this study have the same number of points within them, first, all the linguistic terms used in the evaluations were converted to the numbers in Saaty's scale. Then, Eq. (6) can be used to calculate the consistency ratio (CR).

$$CR = \frac{CI}{RI} \tag{6}$$

where "*RI*" stands for the random index, which varies depending on the number of criteria used in the decision (n), and "*CI*" is the consistency

Table 1
Linguistic scale for IVIF-AHP.

Linguistic terms	IVIFNs
Exactly More Important (EMI)	[0.00, 0.05], [0.90, 0.95]
Perfectly More Important (PMI)	[0.05, 0.10], [0.85, 0.90]
Absolutely More Important (AMI)	[0.10, 0.15], [0.80, 0.85]
Very Strongly More Important (VSI)	[0.15, 0.20], [0.75, 0.80]
Strongly More Important (StMI)	[0.20, 0.25], [0.70, 0.75]
More Important (MI)	[0.25, 0.30], [0.65, 0.70]
Weakly More Important (WMI)	[0.30, 0.35], [0.60, 0.65]
Slightly More Important (SMI)	[0.35, 0.40], [0.55, 0.60]
Exactly Equal Importance (EEI)	[0.40, 0.60], [0.30, 0.40]
Slightly More Unimportant (SEU)	[0.55, 0.60], [0.35, 0.40]
Weakly More Unimportant (WMU)	[0.60, 0.65], [0.30, 0.35]
More Unimportant (MU)	[0.65, 0.70], [0.25, 0.30]
Strongly More Unimportant (SMU)	[0.70, 0.75], [0.20, 0.25]
Very Strongly More Unimportant (VSU)	[0.75, 0.80], [0.15, 0.20]
Absolutely More Unimportant (AMU)	[0.80, 0.85], [0.10, 0.15]
Perfectly More Unimportant (PMU)	[0.85, 0.90], [0.05, 0.10]
Exactly More Unimportant (EMU)	[0.90, 0.95], [0.00, 0.05]

index that is found in Eq. (7).

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (7)$$

Here, "λ_{max}" denotes the largest eigenvector of the matrix. The pairwise comparison matrix is consistent and can be proceeded with if the calculated CR value is less than or equal to 0.1 [65]. In the case of detecting an inconsistent matrix, pairwise comparisons within this matrix should be reviewed.

Step 5. The pairwise comparison matrices of the decision makers are aggregated using Interval-Valued Intuitionistic Fuzzy Weighted Geometric Mean (IVIFWGM) in Eq. (3), giving $\widetilde{C}$ in Eq. (8).

$$\widetilde{C} = \begin{bmatrix} (0.4, 0.6), (0.3, 0.4) & \cdots & \widetilde{c}_{1n} \\ \vdots & \ddots & \vdots \\ \widetilde{c}_{n1} & \cdots & (0.4, 0.6), (0.3, 0.4) \end{bmatrix} \quad (8)$$

Step 6. The average of the IVIFNs in each row of the matrix is found using Eq. (2).

Step 7. Defuzzified values of the rows are calculated by using Eq. (4).

Step 8. Defuzzified values are normalized, giving the local weights. The global weight of the sub-criteria can then be calculated by multiplying their local weights with the weight of their parent criteria.

Step 9. The preference score, PS_i, for alternative i can be calculated using Eq. (9).

$$PS_i = \sum_{j=1}^{n} w_j s_{ij}, \forall i \quad (9)$$

where w_j is the global weight of criterion j and s_{ij} is the defuzzified score value of alternative i considering criterion j. The best alternative is the one having the highest PS_i value.

6. Application and analysis

To provide the readers with a more effortless follow-up and more precise understanding, the step numbers in the application are kept the same as those in the methodology.

Step 1. A hierarchical model for selecting sustainable stationary hydrogen storage applications is proposed. The model consists of four criteria and 15 sub-criteria, as explained in Section 3. Four alternatives were evaluated against this model, as given in Section 4.

Step 2. Three experts with sound international experience on the topic were selected. They used linguistic terms from Table 1 for a couple of optimistic and pessimistic evaluations for each pairwise comparison.

As an example, linguistic pairwise comparisons of Expert 1 for the main criteria are given in Table 2.

Step 3. $\widetilde{A}^k$ was formed by translating corresponding linguistic variables to IVIFNs from Table 1 to fill $\widetilde{A}_{ij}^k$ values above the diagonal of the individual pairwise comparison matrix of expert k (for $k = 1, 2, 3$).

$$\frac{0.3993 + 0.5060 + (1 - 0.4197) + (1 - 0.4940) + 0.3993 \times 0.5060 - \sqrt{(1 - 0.4197)(1 - 0.4940)}}{4} = 0.4129$$

As an example, Expert 1's pairwise comparisons in IVIFNs for the main criteria are given in Table 3.

Step 4. To determine the level of consistency in the fuzzy comparison matrices, the crisp representation of the corresponding IVIFN yielding the conjugate crisp version of the IVIF comparison matrix is given. Table 4 presents a sample for such a conjugate crisp version.

Consistency ratio (CR) calculations of the conjugate pairwise comparison matrices were then completed following Step 4 in the methodology section. The CR of the matrix above, for example, was calculated as 0.06, and the matrix was proven to be consistent.

When any of the conjugate pairwise comparison matrices were found inconsistent, the authors collaborated with the experts to fix the issue until the problem was resolved. Upon the completion of the reviewing process of all the matrices, the matrices were used directly in further calculations.

Step 5. The pairwise comparison matrices of the decision makers were aggregated using IVIFWGM. Experts' IVIF pairwise comparison matrices for the main criteria and the aggregated comparison matrix are given in Tables 5 and 6, respectively.

To illustrate the aggregation process numerically, the calculation of the value of the cell presenting the comparison of Economic Performance vs. Environmental Performance criteria (shaded in Tables 5 and 6) is given as

$$1 - (1 - 0.25)^{\frac{1}{3}} \times (1 - 0.25)^{\frac{1}{3}} \times (1 - 0.35)^{\frac{1}{3}} = 0.6194$$

$$1 - (1 - 0.30)^{\frac{1}{3}} \times (1 - 0.30)^{\frac{1}{3}} \times (1 - 0.40)^{\frac{1}{3}} = 0.6698$$

$$0.65^{1/3} \times 0.65^{1/3} \times 0.55^{1/3} = 0.2797$$

$$0.70^{1/3} \times 0.70^{1/3} \times 0.60^{1/3} = 0.3302$$

As a result of this calculation, the shaded cell in Table 6 is achieved as [0.2849, 0.3351], [0.6148, 0.6649].

Step 6. The average of the IVIFNs in each row of the matrix was found using Eq. (2). Table 7 shows the IVIFWAMs of the rows of the aggregated IVIF pairwise comparison matrix for the main criteria.

To illustrate the calculations, the calculation of the IVIFWAM of Economic Performance is given below.

$$1 - \left((1 - 0.4000)^{1/4} \times (1 - 0.2849)^{1/4} \times (1 - 0.5322)^{1/4} \times (1 - 0.3513)^{1/4}\right) = 0.3993$$

$$1 - \left((1 - 0.6000)^{1/4} \times (1 - 0.3351)^{1/4} \times (1 - 0.5840)^{1/4} \times (1 - 0.4617)^{1/4}\right) = 0.5060$$

$$0.3000^{1/4} \times 0.6148^{1/4} \times 0.3637^{1/4} \times 0.4626^{1/4} = 0.4197$$

$$0.4000^{1/4} \times 0.6649^{1/4} \times 0.4160^{1/4} \times 0.5383^{1/4} = 0.4940$$

Hence, the IVIFWAM of Economic Performance in Table 7 is achieved [0.3993, 0.5060], [0.4197, 0.4940].

Step 7. Defuzzified values for the rows were calculated by using Eq. (4). Defuzzified values of the main criteria, as an example, are given in Table 8.

To illustrate the mathematical operations, the calculation of the score value of the Economic Performance criterion is presented below.

Step 8. Defuzzified values were normalized, giving the local weights. Global weights of the sub-criteria were then calculated by multiplying their local weights with the weight of the corresponding parent criterion (Table 9).

Step 9. The weight of each alternative calculated for each criterion (s_{ij}) and preference scores ($w_j s_{ij}$) were calculated as given in Table 10.

Final preference scores for alternatives (PS_i, for $i = 1, \ldots, 4$) were calculated using Eq. (9). These scores are listed in Table 11.

Table 2
Linguistic pairwise comparisons of Expert 1 for main criteria.

Main Criteria	Economic Performance	Environmental Performance	Social Performance	Technical Performance
Economic Performance	EEI	MU	StMI	SEU
Environmental Performance		EEI	WMI	WMI
Social Performance			EEI	WMU
Technical Performance				EEI

Table 3
Expert 1's pairwise comparisons in IVIFNs for main criteria.

Main Criteria	Economic Performance	Environmental Performance	Social Performance	Technical Performance
Economic Performance	[0.40, 0.60], [0.30, 0.40]	[0.25, 0.30], [0.65, 0.70]	[0.70, 0.75], [0.20, 0.25]	[0.35, 0.40], [0.55, 0.60]
Environmental Performance		[0.40, 0.60], [0.30, 0.40]	[0.60, 0.65], [0.30, 0.35]	[0.60, 0.65], [0.30, 0.35]
Social Performance			[0.40, 0.60], [0.30, 0.40]	[0.30, 0.35], [0.60, 0.65]
Technical Performance				[0.40, 0.60], [0.30, 0.40]

Table 4
Expert 1's conjugate pairwise comparisons for main criteria.

Main Criteria	Economic Performance	Environmental Performance	Social Performance	Technical Performance
Economic Performance	1.00	0.25	2.00	0.50
Environmental Performance	4.00	1.00	3.00	3.00
Social Performance	0.50	0.33	1.00	0.33
Technical Performance	2.00	0.33	3.00	1.00

Table 5
Experts' IVIF pairwise comparison matrices for the main criteria.

Expert	Main Criteria	Economic Performance	Environmental Performance	Social Performance	Technical Performance
EXPERT 1	Economic Performance	[0.40, 0.60], [0.30, 0.40]	[0.25, 0.30], [0.65, 0.70]	[0.55, 0.60], [0.35, 0.40]	[0.35, 0.40], [0.55, 0.60]
	Environmental Performance	[0.65, 0.70], [0.25, 0.30]	[0.40, 0.60], [0.30, 0.40]	[0.60, 0.65], [0.30, 0.35]	[0.60, 0.65], [0.30, 0.35]
	Social Performance	[0.35, 0.40], [0.55, 0.60]	[0.30, 0.35], [0.60, 0.65]	[0.40, 0.60], [0.30, 0.40]	[0.30, 0.35], [0.60, 0.65]
	Technical Performance	[0.55, 0.60], [0.35, 0.40]	[0.30, 0.35], [0.60, 0.65]	[0.60, 0.65], [0.30, 0.35]	[0.40, 0.60], [0.30, 0.40]
EXPERT 2	Economic Performance	[0.40, 0.60], [0.30, 0.40]	[0.25, 0.30], [0.65, 0.70]	[0.35, 0.40], [0.55, 0.60]	[0.30, 0.35], [0.60, 0.65]
	Environmental Performance	[0.65, 0.70], [0.25, 0.30]	[0.40, 0.60], [0.30, 0.40]	[0.60, 0.65], [0.30, 0.35]	[0.55, 0.60], [0.35, 0.40]
	Social Performance	[0.55, 0.60], [0.35, 0.40]	[0.30, 0.35], [0.60, 0.65]	[0.40, 0.60], [0.30, 0.40]	[0.35, 0.40], [0.55, 0.60]
	Technical Performance	[0.60, 0.65], [0.30, 0.35]	[0.35, 0.40], [0.55, 0.60]	[0.55, 0.60], [0.35, 0.40]	[0.40, 0.60], [0.30, 0.40]
EXPERT 3	Economic Performance	[0.40, 0.60], [0.30, 0.40]	[0.35, 0.40], [0.55, 0.60]	[0.65, 0.70], [0.25, 0.30]	[0.40, 0.60], [0.30, 0.40]
	Environmental Performance	[0.55, 0.60], [0.35, 0.40]	[0.40, 0.60], [0.30, 0.40]	[0.70, 0.75], [0.20, 0.25]	[0.55, 0.60], [0.35, 0.40]
	Social Performance	[0.25, 0.30], [0.65, 0.70]	[0.20, 0.25], [0.70, 0.75]	[0.40, 0.60], [0.30, 0.40]	[0.25, 0.30], [0.65, 0.70]
	Technical Performance	[0.30, 0.40], [0.40, 0.60]	[0.35, 0.40], [0.55, 0.60]	[0.65, 0.70], [0.25, 0.30]	[0.40, 0.60], [0.30, 0.40]

Table 6
Aggregated IVIF pairwise comparison matrix for the main criteria.

Main Criteria	Economic Performance	Environmental Performance	Social Performance	Technical Performance
Economic Performance	[0.4000, 0.6000], [0.3000, 0.4000]	[0.2849, 0.3351], [0.6148, 0.6649]	[0.5322, 0.5840], [0.3637, 0.4160]	[0.3513, 0.4617], [0.4626, 0.5383]
Environmental Performance	[0.6194, 0.6698], [0.2797, 0.3302]	[0.4000, 0.6000], [0.3000, 0.4000]	[0.6366, 0.6871], [0.2621, 0.3129]	[0.5673, 0.6174], [0.3325, 0.3826]
Social Performance	[0.3969, 0.4482], [0.5002, 0.5518]	[0.2681, 0.3182], [0.6316, 0.6818]	[0.4000, 0.6000], [0.3000, 0.4000]	[0.3012, 0.3513], [0.5986, 0.6487]
Technical Performance	[0.4987, 0.5620], [0.3476, 0.4380]	[0.3337, 0.3838], [0.5662, 0.6162]	[0.6021, 0.6524], [0.2972, 0.3476]	[0.4000, 0.6000], [0.3000, 0.4000]

Table 7
IVIFWAMs of the rows of the aggregated IVIF pairwise comparison matrix for the main criteria.

Main Criteria	IVIFWAM
Economic Performance	[0.3993, 0.5060], [0.4197, 0.4940]
Environmental Performance	[0.5647, 0.6454], [0.2924, 0.3546]
Social Performance	[0.3441, 0.4410], [0.4880, 0.5590]
Technical Performance	[0.4686, 0.5599], [0.3640, 0.4401]

Table 8
Score values of the main criteria.

Main Criteria	Defuzzified values (DV)
Economic Performance	0.4129
Environmental Performance	0.5629
Social Performance	0.3537
Technical Performance	0.4725

Table 9
The weights of main and sub-criteria.

Main Criteria	Weights of Main Criteria	Sub-Criteria	Local Weights of Sub-Criteria	Global Weights of Sub-Criteria
Economic Performance	0.2291	Capital Cost	0.2996	0.0686
		Operating Cost	0.2877	0.0659
		Levelized cost of hydrogen	0.4127	0.0946
Environmental Performance	0.3124	GHG emissions	0.3025	0.0945
		Land use requirements	0.2262	0.0707
		Water consumption	0.2669	0.0834
		Solid waste generation	0.2044	0.0639
Social Performance	0.1947	Safety	0.2919	0.0573
		Accessibility	0.2526	0.0496
		Ease of use	0.2231	0.0438
		Public acceptance	0.2325	0.0456
Technical Performance	0.2629	Efficiency	0.2548	0.0668
		Energy density	0.2692	0.0706
		Power density	0.2317	0.0608
		Cycle life	0.2442	0.0640

Based on these final preference scores, Compressed hydrogen gas (CHG) was found to be the best alternative, with the highest preference score value of 0.2698. The close values in Table 11 reflect the nuanced and multifaceted nature of the criteria used to evaluate the hydrogen storage alternatives. This scenario is common in complex multicriteria decision analysis (MCDA) exercises like AHP, where various alternatives exhibit competitive advantages across different dimensions. While the AHP process provides a rigorous and systematic framework for evaluation, the final decision might require additional deliberation, especially when the preference scores are closely packed, as seen in this table. Here are several steps and considerations that could guide the final selection process:

- **Thresholding:** Establishing a threshold of acceptance or significance could help delineate the alternatives. For instance, setting a threshold might help identify a clear leader among the alternatives or dismiss certain options that do not meet the threshold.
- **Scenario Analysis:** Evaluating the alternatives under different scenarios might influence decision-making. For instance, scenarios could be constructed based on possible changes in technological advancements, regulatory frameworks, or market conditions.
- **Stakeholder Feedback:** Their input could provide valuable perspectives that help make a more informed selection.
- **Supplementary Criteria:** If necessary, introducing supplementary criteria or sub-criteria might help create a clearer distinction between the alternatives.

By incorporating these additional steps and considerations, decision-makers can navigate the close preference scores, arrive at a more robust selection, and ensure the decision aligns well with the broader sustainability and technical objectives of the hydrogen storage initiative.

6.1. Sensitivity analysis

The contemporary business environment is characterized by its highly dynamic nature, leading to temporal fluctuations that can impact the assessments made by experts regarding the significance of the main criteria. A sensitivity analysis was conducted to assess the robustness of alternative selection outcomes in response to varying preferences for these criteria. This analysis involves systematically altering the weights assigned to the main criteria individually, ranging from 0 to 1 in increments of 0.1. Meanwhile, the weights of the remaining criteria were adjusted proportionally based on the initial results. The results of the sensitivity analysis for the main criteria are presented in Fig. 2.

Notably, the analysis reveals that changes in all main criteria, except Technical Performance, have an influence on the decision, meaning that the decision is sensitive to the changes in the weight of Economic, Environmental, and Social performance, as further detailed below.

In the Economic Performance (Fig. 2a), the leading position of CHG changes at the weight 0.5, and from this point on, UH becomes the most preferred alternative. It can also be observed that MH demonstrates a significant decrease in preference together with increasing criterion weight, whereas UH significantly increases its preference.

The decision appears to be highly affected by alterations in the magnitude of Environmental Performance weight (Fig. 2b). CHG starts with being the most preferred alternative at low criterion weights and leaves its position to UH at the weight of 0.55. UH stays the leading alternative until the weight of 0.9, and from this point on, MH turns out to be the most preferred alternative. The preference scores of UH and MH increase, whereas CHG and CLH decrease steadily.

In the Social Performance (Fig. 2c), UH starts with being the most preferred alternative but keeps its leading position for a noticeably short time. CHG takes over UH's position at the weight of 0.1. UH demonstrates a steep decline, whereas all other alternatives increase their preference scores together with the increasing criterion weight.

Lastly, the decision is not sensitive to the Technical Performance (Fig. 2d), meaning that the most preferred alternative, CHG, remains the same regardless of the changes in the weight of this criterion. It exhibits a very slight increase in performance, whereas the runner-up, UH, loses its performance score slightly.

7. Results and discussion

This section presents the results obtained from applying the Interval-Valued Intuitionistic Fuzzy Analytic Hierarchy Process (IVIF-AHP) method in assessing the sustainability performance of the selected stationary hydrogen storage options. These options include compressed hydrogen gas (CHG), cryogenic liquid hydrogen (CLH), metal hydrides (MH), and underground hydrogen (UH). The results are broken down according to the main and sub-criteria, revealing detailed insights into the strengths and weaknesses of each storage option from multiple perspectives. The outcomes discussed herein are not merely a reflection of numerical assessments, but are also embedded with critical evaluations, interpretations, and discussions aimed at generating actionable insights for decision-makers, stakeholders, and researchers in the hydrogen storage sector. The interplay between the four main criteria and their respective sub-criteria in shaping the sustainability performance of each hydrogen storage option will be explored in detail.

The weights assigned to the main criteria (Fig. 3) reflect the relative significance of different aspects of sustainability in the context of stationary hydrogen storage. In this study, Environmental Performance emerged as the most influential criterion, accounting for 31% of the sustainability evaluation. This result underscores the critical role of environmental stewardship in hydrogen storage applications, echoing the more comprehensive societal and regulatory emphasis on low-carbon, resource-efficient solutions. Reducing GHG emissions,

Table 10
Preference score calculations for alternatives.

Sub-Criteria	Global Weights of Sub Criteria (w_j)	Alternatives	Weights (s_{ij})	Preference Scores ($w_j s_{ij}$)
Capital Cost	0.0686	A1	0.2650	0.0182
		A2	0.2256	0.0155
		A3	0.1171	0.0080
		A4	0.3923	0.0269
Operating Cost	0.0659	A1	0.2747	0.0181
		A2	0.2353	0.0155
		A3	0.3745	0.0247
		A4	0.1154	0.0076
Levelized cost of hydrogen	0.0946	A1	0.2658	0.0251
		A2	0.2326	0.0220
		A3	0.1619	0.0153
		A4	0.3397	0.0321
GHG emissions	0.0945	A1	0.2323	0.0219
		A2	0.1617	0.0153
		A3	0.2660	0.0251
		A4	0.3401	0.0321
Land use requirements	0.0707	A1	0.2241	0.0158
		A2	0.2584	0.0183
		A3	0.3309	0.0234
		A4	0.1866	0.0132
Water consumption	0.0834	A1	0.2770	0.0231
		A2	0.1695	0.0141
		A3	0.3171	0.0264
		A4	0.2364	0.0197
Solid waste generation	0.0639	A1	0.2770	0.0177
		A2	0.2364	0.0151
		A3	0.1695	0.0108
		A4	0.3171	0.0202
Safety	0.0573	A1	0.2149	0.0123
		A2	0.1745	0.0100
		A3	0.3207	0.0184
		A4	0.2898	0.0166
Accessibility	0.0496	A1	0.3383	0.0168
		A2	0.2333	0.0116
		A3	0.2661	0.0132
		A4	0.1623	0.0080
Ease of use	0.0438	A1	0.3403	0.0149
		A2	0.2064	0.0090
		A3	0.3110	0.0136
		A4	0.1423	0.0062
Public acceptance	0.0456	A1	0.3207	0.0146
		A2	0.2898	0.0132
		A3	0.2149	0.0098
		A4	0.1745	0.0080
Efficiency	0.0668	A1	0.2784	0.0186
		A2	0.1684	0.0112
		A3	0.2504	0.0167
		A4	0.3029	0.0202
Energy density	0.0706	A1	0.1631	0.0115
		A2	0.2934	0.0207
		A3	0.3492	0.0247
		A4	0.1943	0.0137
Power density	0.0608	A1	0.3813	0.0232
		A2	0.2629	0.0160
		A3	0.1583	0.0096
		A4	0.1974	0.0120
Cycle life	0.0640	A1	0.2787	0.0178
		A2	0.2290	0.0147
		A3	0.1626	0.0104
		A4	0.3297	0.0211

Table 11
Final preference scores for alternatives.

Alternatives	***PS***
Compressed hydrogen gas (CHG)	0.2698
Cryogenic liquid hydrogen (CLH)	0.2222
Metal hydride (MH)	0.2502
Underground hydrogen (UH)	0.2579

minimizing land use, conserving water, and managing solid waste effectively are fundamental to ensuring the environmental sustainability of these technologies.

Technical performance, with a weight of 26%, is identified as the second most important criterion. The emphasis on technical aspects such as efficiency, energy density, power density, and cycle life resonates with the need for dependable, robust, and high-performing hydrogen storage systems. These technical characteristics directly influence the system's ability to meet energy demand effectively and endure long-term use, hence playing a vital role in the sustainability assessment.

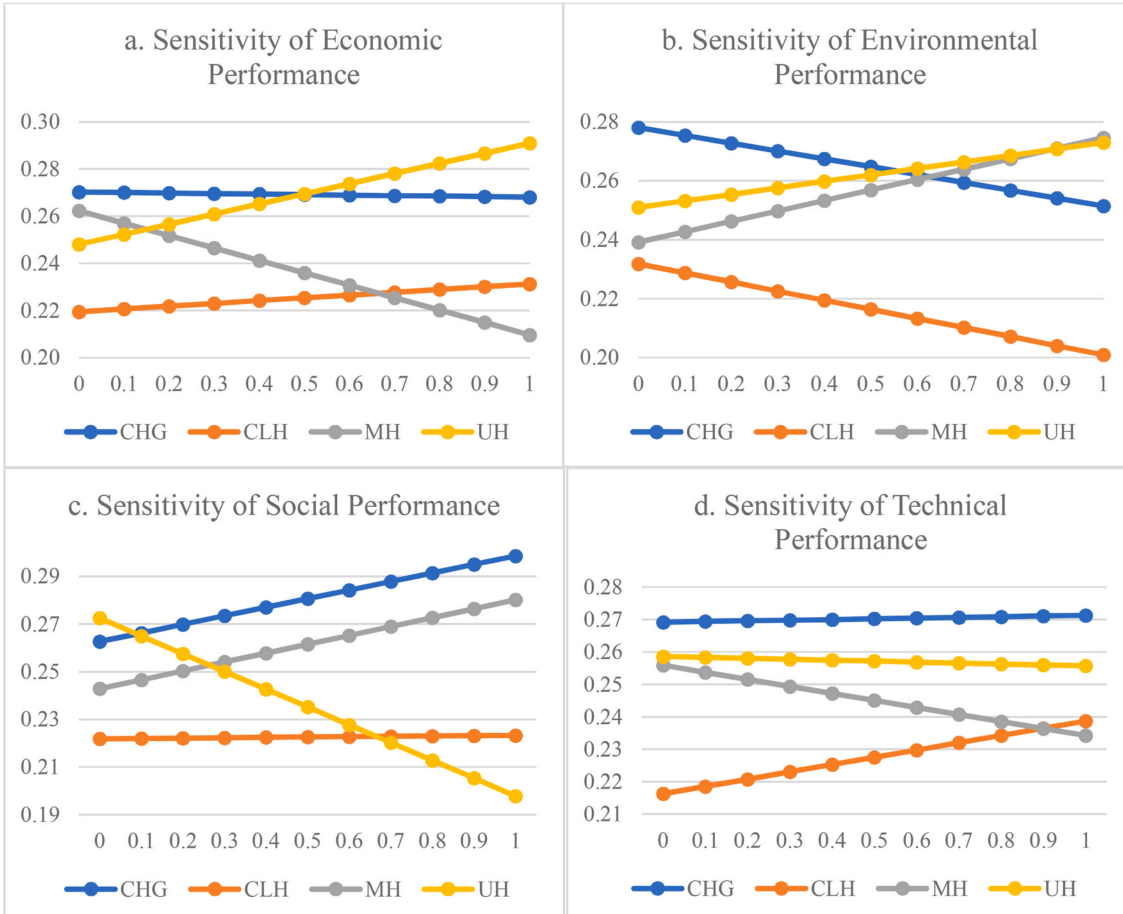

Fig. 2. Sensitivity analysis of the main criteria.

Economic performance, accounting for 23% of the evaluation, highlights the importance of cost-effectiveness in the deployment and operation of hydrogen storage systems. While environmental and technical performances are paramount, the economic viability of these systems is equally crucial for their broader acceptance and integration into the energy market.

Finally, Social Performance carries a weight of 21%, acknowledging the societal implications of hydrogen storage technologies. Safety, accessibility, ease of use, and public acceptance are essential for the successful implementation and scalability of these systems, thereby contributing to their overall sustainability.

In the evolving landscape of energy systems, the traditional dominance of economic considerations is progressively balanced by the imperatives of environmental sustainability and technical robustness. This shift is part of a broader recognition of the energy-economy-environment (3E) nexus, which posits that these three dimensions are interlinked and must be addressed holistically to achieve sustainable development goals. In the context of this study, the ranking of economic values third, after environmental and technical criteria, reflects a nuanced understanding of the 3E nexus and the exigencies of contemporary energy challenges, notably the urgent need to mitigate climate change impacts.

Traditionally driven by the prospect of economic returns, investors are now increasingly confronted with regulatory and market pressures to align their portfolios with climate and sustainability objectives. The emergent paradigm of sustainable investing, embodied in frameworks such as the Environmental, Social, and Governance (ESG) criteria, underscores this trend. Hence, the emphasis on environmental and technical criteria in evaluating hydrogen storage options resonates with the evolving investment ethos that seeks to harmonize financial performance with sustainability imperatives.

Furthermore, the climate crisis has catalyzed a global discourse on the necessity of decarbonizing energy systems, within which hydrogen emerges as a key enabler due to its potential to store and provide clean energy. The technical criteria underscore the efficacy and reliability of hydrogen storage technologies, which are paramount for realizing a hydrogen-based energy ecosystem. Simultaneously, the environmental criteria encapsulate the carbon reduction potential and other ecological impacts of these technologies, aligning with global climate mitigation goals.

In practical implementations, the shift in evaluative criteria might initially meet resistance from investors accustomed to cost-centric assessments. However, the broader societal and market transition towards sustainability is expected to realign investment priorities. Moreover, policy instruments such as carbon pricing, subsidies for clean energy technologies, and stringent environmental regulations can incentivize the adoption of sustainable hydrogen storage technologies, potentially allaying investors' concerns regarding economic viability.

Thus, ranking economic values as third may be emblematic of a broader, forward-looking understanding that aligns with global sustainability aspirations. It beckons a recalibration of investment strategies to accommodate the long-term socioeconomic benefits of transitioning to a low-carbon hydrogen economy, fostering a conducive environment for sustainable investment in hydrogen storage technologies.

The weighting distribution among these criteria reflects the multifaceted nature of sustainability assessments. It also implies that a balanced, comprehensive approach is needed in assessing and

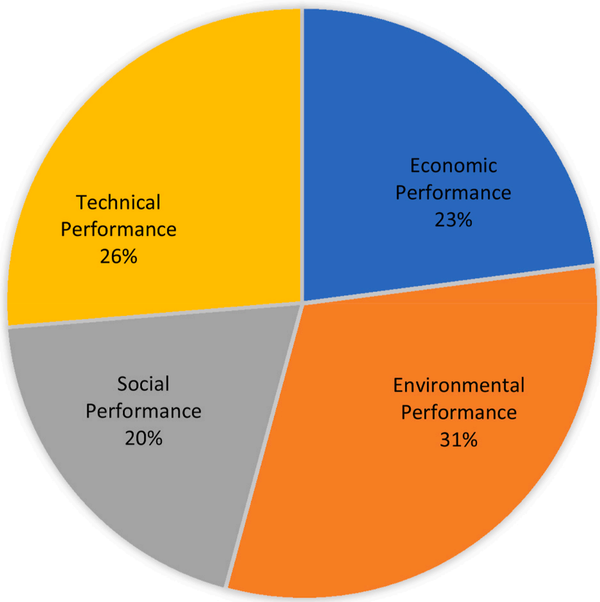

Fig. 3. Weights of the main sustainability assessment criteria for the selected hydrogen storage options.

improving the sustainability performance of stationary hydrogen storage options. While environmental and technical aspects carry slightly more weight, economic and social aspects are also essential and should not be overlooked to achieve genuinely sustainable hydrogen storage solutions. Furthermore, the weightings could shift over time or in different geographical, socioeconomic, or regulatory contexts, highlighting the need for ongoing reassessments in the face of changing conditions and new knowledge.

The distribution of weights amongst the sub-criteria (Fig. 4) within each of the main criteria offers intriguing insights into what factors most heavily influence the overall sustainability evaluation of hydrogen storage options.

Within Economic Performance, which holds 23% weight, the Levelized Cost of Hydrogen (LCOH) has the highest sub-criterion weight at 0.0946, indicating its importance in assessing the economic viability of different hydrogen storage systems. This comprehensive metric encapsulates both Capital Cost (0.0686) and Operating Cost (0.0659) over the lifespan of the storage system, reflecting the long-term economic performance of these options.

For Environmental Performance, contributing 31% weight to the overall sustainability evaluation, GHG emissions stand out with a sub-criterion weight of 0.0945, emphasizing the importance of low-carbon solutions in the context of climate change mitigation. Other sub-criteria, such as Land Use Requirements (0.0707), Water Consumption (0.0834), and Solid Waste Generation (0.0639), are also significant, highlighting the need to manage environmental resources and impacts efficiently.

Within Social Performance (20% weight), safety has the highest weight at 0.0573, reflecting the importance of ensuring secure operation and handling of hydrogen storage systems for both workers and the broader community. Accessibility (0.0496), Ease of Use (0.0438), and Public Acceptance (0.0456) are also vital for the successful implementation and social acceptance of these technologies.

Technical performance, representing 26% of the sustainability evaluation, prioritizes Energy Density (0.0706), followed closely by Efficiency (0.0668). These sub-criteria underscore the need for high-performing and efficient storage solutions to ensure optimal functionality and usability. Power Density (0.0608) and Cycle Life (0.064) also play critical roles in the technical assessment of these systems.

In summary, these sub-criteria weights provide a detailed understanding of specific performance considerations critical to the sustainable deployment and operation of stationary hydrogen storage systems. They highlight the multifaceted nature of sustainability performance, demonstrating the importance of considering a broad range of economic, environmental, social, and technical factors in selecting hydrogen storage options.

This analysis underlines the intricate nature of sustainability assessment for hydrogen storage technologies. The nuanced weighting of different sub-criteria reflects the diverse considerations that must be factored into decisions regarding the development and deployment of sustainable hydrogen storage solutions. Importantly, these weights might need to be adjusted over time or across different contexts, highlighting the need for adaptable and responsive assessment strategies.

The results of this study outline the weight distribution among different hydrogen storage options (Table 10) based on various economic, environmental, social, and technical sub-criteria. The findings highlight the intricate nature of decision-making in sustainable energy systems, such as hydrogen storage. Each storage method has its strengths and weaknesses, providing valuable insights for decision-makers. However, understanding these trade-offs is not straightforward and

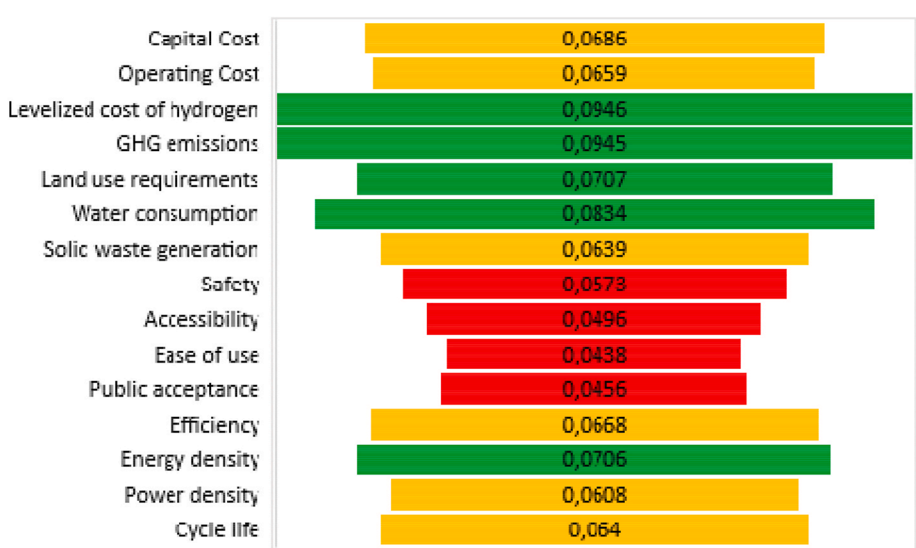

Fig. 4. Distribution of weights amongst the sub-sustainability assessment criteria for the selected hydrogen storage options.

requires careful contemplation of the results.

Starting with the economic performance, Metal Hydride (MH) storage has the highest capital cost, making it the most expensive option for initial setup. Conversely, Underground Hydrogen (UH) storage features the lowest capital cost. In terms of operating costs, UH storage appears to be the costliest, while MH storage has the least operating cost. This outcome suggests a possible trade-off between capital and operating costs between these two options. For the levelized cost of hydrogen, again, MH storage leads with a higher cost, while UH has the lowest levelized cost. The solid economic performance of Underground Hydrogen (UH) in terms of capital and levelized costs could be due to the existing natural gas infrastructure that can be repurposed for hydrogen storage, reducing initial investment requirements. However, its relatively high operating cost may reflect the potential maintenance and monitoring costs of such underground systems. Future research could focus on reducing these operational costs, potentially making UH a more attractive option economically.

Examining the environmental performance, Cryogenic Liquid Hydrogen (CLH) has the highest GHG emissions, which might be linked to the energy-intensive process of hydrogen liquefaction. UH storage, however, has the lowest emissions. In terms of land use requirements, UH storage requires the most, probably due to the immense geological structures needed, while MH storage requires the least. CLH has the highest water consumption, while MH has the least. Solid waste generation is highest for MH, likely due to the use of metal alloys, and lowest for UH. UH's superior performance in terms of GHG emissions may be attributable to the minimal energy needed for injection and retrieval from subsurface storage. However, the relatively high land use by UH might be due to the physical size of the systems and the necessary infrastructure. This requirement implies that the placement of UH systems may be more restricted, especially in densely populated areas. UH also requires large underground volumes that can be used for gas storage purposes. MH systems look more promising for urban areas. Future research directions might include exploring more compact and efficient designs for MH storage systems with less solid waste.

For social performance, safety concerns are most serious for CLH, possibly due to the handling of extremely cold liquid hydrogen, while MH storage is seen as the safest. In terms of accessibility, UH storage scores the lowest, potentially due to the restricted availability of suitable geological structures, whereas Compressed Hydrogen Gas (CHG) scores the highest. Ease of use is lowest for UH storage and highest for CHG. Public acceptance is also highest for CHG storage and lowest for UH, which might be linked to perceptions of safety and accessibility. The relatively high safety score for MH could be due to its lower operating pressures and temperatures, reducing the risk of leaks or explosions. However, it is worth noting that public acceptance may vary by region, influenced by factors such as familiarity with technology, perceived safety, and local community engagement. The high scores for CHG in accessibility and ease of use might be due to the technology's maturity and widespread use. Policymakers should consider the local context when implementing hydrogen storage solutions, and more research is needed into effective community engagement strategies for energy infrastructure.

Lastly, for technical performance, UH exhibits the highest efficiency, possibly due to its lower energy input requirement, while CHG has the lowest efficiency. In terms of energy density, MH leads, with CHG having the lowest. CHG storage offers the highest power density, with MH the lowest. For cycle life, UH again has the highest score, indicating the most extended expected operational lifespan, whereas MH storage has the shortest cycle life. The superior power density of CHG may reflect the rapid gas release possible from high-pressure systems, delivering high power output. The high energy density of MH could be attributed to the high hydrogen content in metal hydrides. However, this often comes at the cost of weight and size, which could limit their applications. In contrast, UH's high efficiency and cycle life scores suggest it has excellent long-term stability and less energy loss during operation. These strengths may be due to the naturally insulated and large-capacity characteristics of underground storage.

The results provide a nuanced picture of the strengths and weaknesses of different hydrogen storage options. Each option presents trade-offs between various economic, environmental, social, and technical factors. The challenge is to find a balance that meets specific application needs while contributing to the broader sustainability goals. These insights can guide decision-makers in prioritizing specific research, development, and policy efforts toward more sustainable hydrogen storage technologies.

These considerations underscore that the best hydrogen storage option will depend on the specific circumstances and priorities of a given application. Future research should continue to explore methods to optimize these storage technologies across these criteria, while policymakers should consider a holistic set of factors in their decision-making process.

The results highlight the overall sustainability performance scores for the selected hydrogen storage options (Fig. 5). These results provide an integrated view of the four main criteria: economic, environmental, social, and technical performances. This overall score represents a holistic measure of sustainability, encompassing a variety of factors considered in this study.

CHG achieves the highest sustainability performance score (0.27), indicating that it may be the most sustainable option overall among the evaluated technologies. This outcome might be due to its good performance in several sub-criteria, such as accessibility, ease of use, and

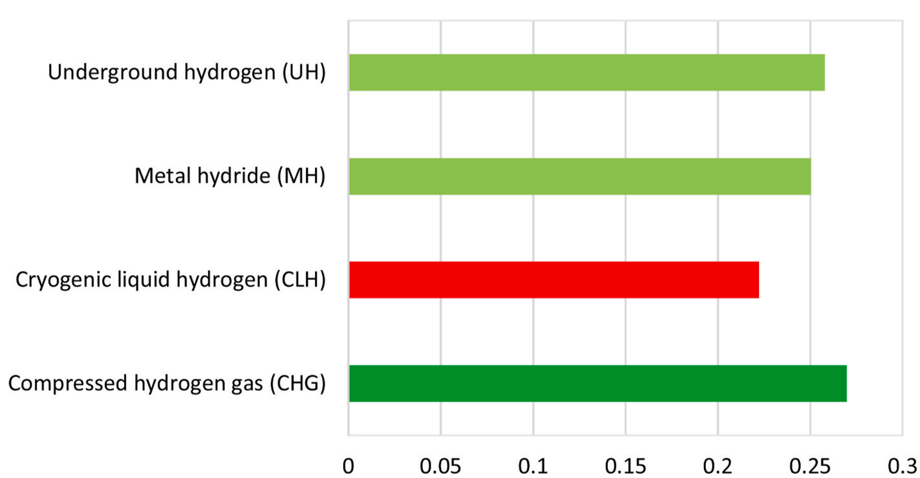

Fig. 5. Overall sustainability performance scores for the selected hydrogen storage options.

power density. However, its relatively high GHG emissions and land use requirement, possible safety issues due to high pressures, and lower energy density compared to other technologies suggest potential areas for improvement. Future research and technology development in this area could focus on optimizing these aspects to further improve the sustainability of CHG.

MH and UH storage options show similar sustainability performance scores (0.25 and 0.26, respectively), indicating a comparable level of overall sustainability. MH storage's low operating cost, safety, accessibility, and ease of use may have balanced out its higher capital costs and low power density. UH storage, with its low capital cost and longer lifetime, offers a viable alternative despite lower efficiency and cycle life. Despite MH's relative strength in safety, energy density, and low land requirements, it has lower public acceptance, reflecting the trade-offs in assessing sustainability. Similarly, while UH performed well economically and environmentally, it lagged in terms of social performance, particularly in accessibility and ease of use. These results suggest that while these technologies have promising aspects, they also have significant areas for improvement.

CLH storage has the lowest sustainability performance score of 0.22. This outcome is potentially reflecting its lower scores across several sub-criteria, such as GHG emissions, land use requirements, and safety. The results might suggest that, despite its advantages in specific areas like energy density, the overall sustainability of CLH is currently less than other options. Future efforts could explore ways to mitigate these issues, perhaps through technological advancements or new operational practices.

These scores demonstrate the complex interplay of multiple factors in determining the sustainability of hydrogen storage options. They underscore the need to address not just one or two factors but rather the complete range of economic, environmental, social, and technical criteria to enhance the overall sustainability performance. The challenge for policymakers, researchers, and industry is to collaboratively address these various aspects, whether it is through improved technology, effective regulation, public outreach, or other means. Also, these scores offer a valuable tool for decision-makers to assess and select the most suitable hydrogen storage options based on the specific sustainability goals and context of their projects.

The sustainability performance scores help guide decision-making, but it is essential to remember that the 'best' choice will depend on the specific circumstances and priorities of the project at hand. Furthermore, as technology and societal preferences evolve, these scores will need to be updated to reflect the changing landscape. Future research should continue to refine these evaluation metrics and develop ways to enhance the sustainability of all hydrogen storage options.

In the related literature, Karatas [19] and İlbahar et al. [18] also dealt with the hydrogen storage option selection problem. Among the reviewed studies, it is evident that Karatas [19] predominantly focused on technical criteria to find the most appropriate hydrogen storage option by considering reliability, storage loss and leak, capacity, total system cost, and weight criteria. This study adopts a single-level hierarchy, which does not address the triple-bottom line of sustainability. Thus, it ignores the economic, environmental, and social dimensions. İlbahar et al. [18], on the other hand, proposed an MCDM model in which four main criteria were taken into account: technical, economic, environmental, and social. The implementation of this study was carried out in Turkey, and the importance levels of the criteria emerged as follows: technical, economic, social, and environmental, respectively. However, the model proposed in our study is an internationally generic model, and experts with international competence in terms of sustainability took part. This model yielded in a difference from the results of İlbahar et al. [18], where the environmental performance emerged as the most crucial criterion in the model. The order of the other criteria remains the same. This result highlights the rapidly increasing importance of the concept of sustainability in the international arena due to global warming.

Finally, a sensitivity analysis was conducted, providing valuable insights into how the assessment of the different hydrogen storage options responds to changes in the weightings assigned to the main criteria: Economic Performance, Environmental Performance, Social Performance, and Technical Performance.

The sensitivity analysis is a critical tool to assess the robustness of the findings and understand how changing the weights of the main criteria impacts the ranking of the hydrogen storage options. The results of this analysis are illuminating, as they reveal how shifts in the relative importance of these criteria can change the overall ranking of the hydrogen storage options. This practice is especially beneficial in the modern business environment marked by rapid changes and uncertain ties.

In terms of Economic Performance, the analysis found that while CHG initially leads, its position is usurped by UH when the weight assigned to this criterion exceeds 0.5. This outcome indicates that if economic considerations become more important, the attractiveness of UH over CHG increases. This shift may be due to UH's superior capital and operating costs, as reflected in the original results. Conversely, MH showed a decline in preference as the weight for Economic Performance increased, perhaps due to its higher capital and operating costs.

For Environmental Performance, the sensitivity analysis also revealed notable shifts in preference. Initially, CHG is most preferred at lower weights, but UH takes the lead once the weight exceeds 0.55. Interestingly, MH becomes the most preferred alternative at exceedingly high weights (0.9), suggesting that MH might be favored in scenarios where environmental considerations are paramount.

Social Performance showed UH as the initial leader, but its lead was short-lived, with CHG taking over as soon as the weight hit 0.1. This abrupt shift may reflect CHG's higher scores in accessibility, ease of use, and public acceptance, all of which are critical aspects of Social Performance.

Interestingly, the sensitivity analysis found no significant influence on the decision for Technical Performance. CHG remained the preferred option regardless of changes in the weight of this criterion. This result suggests a level of robustness in the initial ranking, at least from a technical perspective, but also raises questions about whether other aspects, such as safety, cycle life, and energy density, are balanced in this category.

Overall, the sensitivity analysis highlights the need for comprehensive multicriteria evaluations and offers valuable insights into the decision-making process. It also underscores the importance of considering the variable and dynamic nature of the factors that can impact the sustainability of hydrogen storage options. These insights can inform decision-makers to account for potential changes in criteria weights over time and to devise flexible and robust strategies accordingly.

The Interval-Valued Intuitionistic Fuzzy Analytic Hierarchy Process (IVIF-AHP) methodology employed in this study is inherently adaptive and lends itself to the evolving landscape of hydrogen storage technologies. In the event of significant technical breakthroughs in Compressed Hydrogen Gas (CHG), Cryogenic Liquid Hydrogen (CLH), Metal Hydride (MH), and Underground Hydrogen (UH) technologies, the IVIF-AHP framework can be readily re-deployed to assimilate the newly emerged technological parameters and performance metrics.

The robustness of IVIF-AHP lies in its capability to accommodate diverse criteria and sub-criteria, allowing for the incorporation of updated, nuanced, or entirely new data points reflective of technological advancements. Moreover, its underpinning fuzzy logic facilitates the capture of inherent uncertainties and expert subjectivities that might accompany the assessment of emerging technologies or novel technical features.

As technical breakthroughs unfold, the weights and preference scores within the IVIF-AHP framework can be re-evaluated and updated by experts in the field, ensuring that the decision-making process remains grounded in the most current and accurate technological data. This update includes re-evaluating the relative importance of criteria and sub-criteria based on the latest technological paradigms and stakeholder priorities.

Furthermore, the methodology's transparency and systematic nature ensure a traceable decision-making pathway, allowing stakeholders to readily discern how technological advancements have been factored into the revised analysis and how they affect the comparative sustainability performance of the various hydrogen storage options.

Thus, the IVIF-AHP method not only accommodates but also thrives on the infusion of fresh technological insights, making it a reliable and versatile tool for continually assessing and comparing hydrogen storage technologies in a fast-evolving technical and sustainability-oriented landscape.

It should be noted that this study focuses on assessing the sustainability of hydrogen storage methods for stationary applications. In evaluating hydrogen storage technologies using the Fuzzy Analytic Hierarchy Process (AHP) framework, it is imperative to account for varying application scenarios that could significantly sway the suitability and efficacy of each storage solution. Tailoring the Fuzzy AHP criteria and sub-criteria to reflect the requirements and constraints of diverse application scenarios — such as urban settings versus transportation sectors — can offer more accurate comparative insights. For instance, introducing scenario-specific sub-criteria, adjusting criteria weightings based on scenario requisites, or even conducting separate Fuzzy AHP analyses for different application scenarios could provide a nuanced understanding. Engaging domain experts to validate these scenario-tailored models, alongside conducting sensitivity analyses to gauge how scenario assumption alterations affect technology rankings, can further refine the decision-making process. Such an adaptable approach enhances the robustness of the Fuzzy AHP framework in addressing the multifaceted considerations intrinsic to hydrogen storage technology selection. It assists stakeholders in making well-informed, scenario-aligned decisions toward advancing sustainable hydrogen storage solutions.

8. Conclusions and recommendations

In concluding our investigation, we have highlighted the sustainability attributes of various hydrogen storage technologies - Compressed Hydrogen Gas (CHG), Cryogenic Liquid Hydrogen (CLH), Metal Hydride (MH), and Underground Hydrogen (UH). Through the lens of a multi-criteria decision-making paradigm, our extensive analysis unveiled CHG as the most sustainable choice when gauging the weighted dimensions of economic, environmental, social, and technical performance. Notably, CHG secured a preference score of 0.2698, underlining its superior standing amidst other contenders: CLH (0.2222), MH (0.2502), and UH (0.2579). The economic feasibility, accessibility, user-friendliness, and public acceptance of CHG bolstered its appeal, retaining its technical edge even amidst varied sensitivity analysis scenarios.

These findings bear considerable weight for energy policy formulation and hydrogen infrastructure blueprinting, indicating the current preference for CHG as a balanced and sustainable hydrogen storage solution that adeptly synergizes economic, environmental, social, and technical facets. Nevertheless, the sensitivity analysis underscores a nuanced reality; a shift in environmental focus could tip the scales in favor of Metal Hydride (MH) storage.

In light of these outcomes, we advocate for a vigilant, adaptable stance from policymakers and stakeholders in appraising hydrogen storage technologies. The demonstrated fluidity in preference hinged on the weighting of evaluative criteria aside from technical performance calls attention to the requisite of a robust, flexible planning ethos in energy infrastructure development.

Moreover, this study emboldens the dynamic character of hydrogen storage sustainability, poised on the cusp of technological evolution, policy shifts, and evolving societal values. The ensuing narrative urges continuous research, reassessment, and updating of the decision-making framework to stay in step with the progressive sustainability benchmarks.

We propose a granular examination of hydrogen storage solutions in future studies. Delving into the effects of storage scale and duration on sustainability indices could further refine the multicriteria decision-making framework to specific scenarios, amplifying its practical relevance and aiding a tailored deployment of hydrogen storage infrastructures.

Declaration of competing interest

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

References

[1] Sharma S, Agarwal S, Jain A. Significance of hydrogen as economic and environmentally friendly fuel. Energies 2021;14(21):73–89.
[2] El-Shafie M, Kambara S. Recent advances in ammonia synthesis technologies: toward future zero carbon emissions. Int J Hydrogen Energy 2023;48(30): 11237–73.
[3] Hassan IA, Ramadan HS, Saleh MA, Hissel D. Hydrogen storage technologies for stationary and mobile applications: review, analysis and perspectives. Renew Sustain Energy Rev 2021;149:111311.
[4] Chakraborty S, Kumar NM, Jayakumar A, Dash SK, Elangovan D. Selected aspects of sustainable mobility reveals implementable approaches and conceivable actions. Sustainability 2001;13(22):12918.
[5] Kokkinos K, Nathanail E, Gerogiannis V, Moustakas K, Karayannis V. Hydrogen storage station location selection in sustainable freight transportation via intuitionistic hesitant decision support system. Energy 2022;260:125008.
[6] Gao J, Men H, Guo F, Liang P, Fan Y. A multicriteria decision-making framework for the location of photovoltaic power coupling hydrogen storage projects. J Energy Storage 2021;44:103469.
[7] Wu Y, He F, Zhou H, Wu C, Liu F, Tao Y, Xu C. Optimal site selection for distributed wind power coupled hydrogen storage project using a geographical information system based multicriteria decision-making approach: a case in China. J Clean Prod 2021;299:126905.
[8] Iordache M, Schitea D, Deveci M, Akyurt İZ, Iordache I. An integrated ARAS and interval type-2 hesitant fuzzy sets method for underground site selection: seasonal hydrogen storage in salt caverns. J Petrol Sci Eng 2019;175:1088–98.
[9] Narayan Muduli Amoorthy S, Ramya L, Baleanu D, Kureethara JV, Annapoorani V. Application of normal wiggly dual hesitant fuzzy sets to site selection for hydrogen underground storage. Int J Hydrogen Energy 2019;44(54):28874–92.
[10] Deveci M. Site selection for hydrogen underground storage using interval type-2 hesitant fuzzy sets. Int J Hydrogen Energy 2018;43(19):9353–68.
[11] Lewandowska-Smierzchalska J, Tarkowski R, Uliasz-Misiak B. Screening and ranking framework for underground hydrogen storage site selection in Poland. Int J Hydrogen Energy 2018;43(9):4401–14.
[12] Sun D, Guo D, Xie D. Using multicriteria decision making to evaluate the risk of hydrogen energy storage and transportation in cities. Sustainability 2023;15:1088.
[13] Uliasz-Misiak B, Lewandowska-Smierzchalska J, Matula R. Selection of underground hydrogen storage risk assessment techniques. Energies 2021;14:8049.
[14] Wu Y, Chu H, Xu C. Risk assessment of wind-photovoltaic-hydrogen storage projects using an improved fuzzy synthetic evaluation approach based on cloud model: a case study in China. J Energy Storage 2021;38:102580.
[15] Yi L, Li T. Linguistic hesitant fuzzy sets and cloud model based risk assessment of gaseous hydrogen storage in China. In: Shahnia F, Deilami S, editors. ICPES 2019. Lecture notes in electrical engineering, vol. 669. Singapore: Springer; 2020.
[16] Guo F, Gao J, Liu H, He P. A hybrid fuzzy investment assessment framework for offshore wind-photovoltaic-hydrogen storage project. J Energy Storage 2022;45: 103757.
[17] Wu Y, Wu C, Zhou J, He F, Xu C, Zhang B, Zhang T. An investment decision framework for photovoltaic power coupling hydrogen storage project based on a mixed evaluation method under intuitionistic fuzzy environment. J Energy Storage 2020;30:101601.
[18] İlbahar E, Çolak M, Karaşan A, Kaya İ. A combined methodology based on Z-fuzzy numbers for sustainability assessment of hydrogen energy storage systems. Int J Hydrogen Energy 2022;47(34):15528–46.
[19] Karatas M. Hydrogen energy storage method selection using fuzzy axiomatic design and analytic hierarchy process. Int J Hydrogen Energy 2020;45(32): 16227–38.
[20] Acar C, Beskese A, Temur GT. Sustainability analysis of different hydrogen production options using hesitant fuzzy AHP. Int J Hydrogen Energy 2018;43(39): 18059–76.
[21] Montignac F, Mousseau V, Bouyssou D, Aloulou MA, Rousval B, Damart S. An MCDA approach for evaluating hydrogen storage systems for future vehicles. In: Bisdorff R, Dias L, Meyer P, Mousseau V, Pirlot M, editors. Evaluation and decision models with multiple criteria. International handbooks on information systems. Berlin, Heidelberg: Springer; 2015.
[22] Gim B, Kim JW. Multicriteria evaluation of hydrogen storage systems for automobiles in Korea using the fuzzy analytic hierarchy process. Int J Hydrogen Energy 2014;39:7852–8.

[23] Gumus AT, Yayla AY, Çelik E, Yildiz A. A combined fuzzy-AHP and Fuzzy-GRA methodology for hydrogen energy storage method selection in Turkey. Energies 2013;6:3017–32.
[24] Wu Y, Xu C, Zhang B, Tao Y, Li X, Chu H, Liu F. Sustainability performance assessment of wind power coupling hydrogen storage projects using a hybrid evaluation technique based on interval type-2 fuzzy set. Energy 2019;179:1176–90.
[25] Usman MR. Hydrogen storage methods: review and current status. Renew Sustain Energy Rev 2022;167:112743.
[26] Tashie-Lewis BC, Nnabuife SG. Hydrogen production, distribution, storage and power conversion in a hydrogen economy-a technology review. Chem Eng J Adv 2021;8:100172.
[27] Muduli RC, Kale P. Silicon nanostructures for solid-state hydrogen storage: a review. Int J Hydrogen Energy 2023;48(4):1401–39.
[28] Tan KM, Babu TS, Ramachandaramurthy VK, Kasinathan P, Solanki SG, Raveendran SK. Empowering smart grid: a comprehensive review of energy storage technology and application with renewable energy integration. J Energy Storage 2021;39:102591.
[29] Zhang T, Uratani J, Huang Y, Xu L, Griffiths S, Ding Y. Hydrogen liquefaction and storage: recent progress and perspectives. Renew Sustain Energy Rev 2023;176:113204.
[30] Chatterjee S, Parsapur RK, Huang KW. Limitations of ammonia as a hydrogen energy carrier for the transportation sector. ACS Energy Lett 2021;6(12):4390–4.
[31] Otto M, Chagoya KL, Blair RG, Hick SM, Kapat JS. Optimal hydrogen carrier: holistic evaluation of hydrogen storage and transportation concepts for power generation, aviation, and transportation. J Energy Storage 2022;55:105714.
[32] Dewangan SK, Mohan M, Kumar V, Sharma A, Ahn B. A comprehensive review of the prospects for future hydrogen storage in materials application and outstanding issues. Int J Energy Res 2022;46(12):16150–77.
[33] Abe JO, Popoola API, Ajenifuja E, Popoola OM. Hydrogen energy, economy and storage: review and recommendation. Int J Hydrogen Energy 2019;44(29):15072–86.
[34] Lamb KE, Webb CJ. A quantitative review of slurries for hydrogen storage-Slush hydrogen, and metal and chemical hydrides in carrier liquids. J Alloys Compd 2022:164235.
[35] Navaid HB, Emadi H, Watson M. A comprehensive literature review on the challenges associated with underground hydrogen storage. Int J Hydrogen Energy 2023;48(28):10603–35.
[36] Zivar D, Kumar S, Foroozesh J. Underground hydrogen storage: a comprehensive review. Int J Hydrogen Energy 2021;46(45):23436–62.
[37] Abdin Z, Khalilpour K, Catchpole K. Projecting the levelized cost of large scale hydrogen storage for stationary applications. Energy Convers Manag 2022;270:116241.
[38] Saaty TL, Özdemir MS. How many judges should there be in a group? Ann Data Sci 2014;1:359–68.
[39] Ziemba P, Piwowarski M, Nermend K. Remote work in post-pandemic reality-multi-criteria evaluation of teleconferencing software. Sustainability 2023;15:9919.
[40] Pereira V, Bamel U. Charting the managerial and theoretical evolutionary path of AHP using thematic and systematic review: a decadal (2012-2021) study. Ann Oper Res 2023;326(2):635–51.
[41] Russo FSM, Comanho R. Criteria in AHP: a systematic review of literature. Proc Comput Sci 2015;55:1123–32.
[42] Saaty TL. Decision making with the analytic hierarchy process. Int J Serv Sci 2008;1(1):83–98.
[43] Vaidya OS, Kumar S. Analytic hierarchy process: an overview of applications. Eur J Oper Res 2006;169:1–29.
[44] Forman E, Gass S. The analytic hierarchy process: an exposition. Oper Res 2001;49:469–86.
[45] Govindan K, Jepsen MB. ELECTRE: a comprehensive literature review on methodologies and applications. Eur J Oper Res 2016;250(1):1–29.
[46] Figueira JR, Greco S, Roy B, Slowinski R. An overview of ELECTRE methods and their recent extensions. J Multi-Criteria Decis Anal 2013;20:61–85.
[47] Ishak A, Asfriyati Akmaliah V. Analytical hierarchy process and PROMETHEE as decision making tool: a review. IOP Conf Ser Mater Sci Eng 2019;505(1):12085.
[48] Behzadian M, Kazemzadeh RB, Albadvi A, Aghdasi A. PROMETHEE: a comprehensive literature review on methodologies and applications. Eur J Oper Res 2010;200(1):198–215.
[49] Çelikbilek Y, Tüysüz F. An in-depth review of theory of the TOPSIS method: an experimental analysis. J Manag Analytics 2020;7(2):281–300.
[50] Behzadian M, Otaghsara SK, Yazdani M, Ignatius J. A state-of the-art survey of TOPSIS applications. Expert Syst Appl 2012;39(17):13051–69.
[51] Beskese A, Corum A, Anolay M. A model proposal for ERP system selection in automotive industry. Int J Indus Eng: Theory, Appl Prac 2019;26(3):317–42.
[52] Torfi F, Farahani RZ, Rezapour S. Fuzzy AHP to determine the relative weights of evaluation criteria and Fuzzy TOPSIS to rank the alternatives. Appl Soft Comput 2010;10(2):520–8.
[53] Wu J, Huang HB, Cao QW. Research on AHP with interval-valued intuitionistic fuzzy sets and its application in multi-criteria decision making problems. Appl Math Model 2013;37(24):9898–906.
[54] Fahmi A, Derakhshan A, Kahraman C. Human resources management using interval valued intuitionistic fuzzy analytic hierarchy process. Fuzzy Syst Conf 2015:1–5.
[55] Cebi S, Ilbahar E. Warehouse risk assessment using interval valued intuitionistic fuzzy AHP. Int J Analy Hierar Proc 2018;10(2):243–53.
[56] Büyüközkan G, Havle CA, Feyzioğlu F. A new digital service quality model and its strategic analysis in aviation industry using interval-valued intuitionistic fuzzy AHP. J Air Transport Manag 2020;86:101817.
[57] Büyüközkan G, Havle CA, Feyzioğlu F. Digital competency evaluation of low-cost airlines using an integrated IVIF AHP and IVIF VIKOR methodology. J Air Transport Manag 2021;91:101998.
[58] Lu X, Lu J, Yang X, Chen X. Assessment of urban mobility via a pressure-state-response (PSR) Model with the IVIF-AHP and FCE methods: a case study of Beijing, China. Sustainability 2022;14(5):3112.
[59] Kokoç M, Ersöz S. New score and accuracy function for IVIF sets and their applications to AHP for MCGDM. Cybern Syst 2022;53(3):257–81.
[60] Xu Z. Intuitionistic fuzzy aggregation operators. IEEE Trans Fuzzy Syst 2007;15(6):1179–87.
[61] Aydin N, Seker S. WASPAS based MULTIMOORA method under IVIF environment for the selection of hub location. J Entrepren Inf Manag 2020;33:1233–56.
[62] Saaty TL. How to make a decision: the analytic hierarchy process. Eur J Oper Res 1990;48(1):9–26.
[63] Erdoğan M, Kaya İ. A combined fuzzy approach to determine the best region for a nuclear power plant in Turkey. Appl Soft Comput 2016;39:84–93.
[64] Yildiz D, Temur GT, Beskese A, Bozbura FT. A spherical fuzzy analytic hierarchy process based approach to prioritize career management activities improving employee retention. J Intell Fuzzy Syst 2020;39(5):603–6618.
[65] Saaty TL. Decision making-the analytic hierarchy and network processes (AHP/ANP). J Syst Sci Syst Eng 2004;13(1):1–35.