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Sustainable Hydrogen Production: A Decision-Making Approach Using VIKOR and Intuitionistic Hypersoft Sets

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Abstract: In decision-making scenarios, challenges often arise from closely knitted criteria or inherent uncertainties. Such uncertainties prominently pervade the realm of sustainable energy, particularly concerning hydrogen generation systems. A critical need is identified to elucidate the efficiency, costs, and environmental implications of these technologies as a shift towards a low-carbon economy is pursued. In this study, the interdependencies among decision-making variables were examined, revealing their collective influence and correlations. By utilizing the framework of Intuitionistic Hypersoft Sets (IHSSs), uncertainties were addressed, multi-criteria decision-making (MCDM) was harnessed, technological selection was facilitated, resource allocation was optimized, and environmental ramifications were assessed. The primary objective of this research was to decipher the conundrum of choosing among multiple hydrogen production methodologies. Such an approach fosters the adoption of environmentally conducive hydrogen production methods, heralding a shift towards a greener energy future. Notably, further research could probe into methodologies like AHP and TOPSIS in a neutrosophic context, offering tantalizing avenues for exploration.

Keywords: Aggregate operators; Soft set; Hypersoft set; Decision-making; Hydrogen generation techniques; multi-criteria decision-making; VIKOR Method; Intuitionistic Hypersoft Sets

1 Introduction

In 1965, the theory of fuzzy set and membership was first introduced by Zadeh [1]. This pioneering work rapidly garnered attention and subsequently laid the foundation for myriad technologies integral to modern convenience. It was posited that membership values could be categorized into four distinct forms: single-valued fuzzy numbers, multiple-valued fuzzy numbers, bipolar fuzzy numbers, interval-valued fuzzy numbers, and rough sets. Consequently, new set structures emerged, including the single-valued fuzzy set (SVFS), multiple-valued fuzzy set (MVFS), bi-polar fuzzy set (BPS), Turksen IVFS (interval-valued fuzzy set), m-polar interval-valued fuzzy set (m-PIVFS), and fuzzy rough set (FRS) [2–7].

Expanding upon traditional fuzzy set theory, intuitionistic sets, or more commonly, intuitionistic fuzzy sets (IFS), were developed in the mid-1980s [8]. Unlike conventional fuzzy sets which employ solely membership values, IFS integrates membership, non-membership, and a hesitation value. This hesitation value captures the inherent ambiguity or uncertainty regarding set membership, thus making IFS more apt at managing situations with inadequate data for precise membership value determination. Consequently, by considering both membership and non-membership degrees, intuitionistic sets offer a robust framework for addressing ambiguities in decision-making processes.

Operational rules and decision-making methodologies for MCDM were subsequently introduced as an extension of IFS, leading to the development of the Pythagorean fuzzy set (PFS) [9, 10]. In an endeavor to address uncertain and inconsistent scenarios, Smarandache [11] introduced the neutrosophic set (NS) in 1998 [12]. An amalgamation of intuitionistic fuzzy and soft sets was later formulated, termed intuitionistic fuzzy soft set (IFSS), which encompasses parameters denoting data validity and promotes optimized decision-making [13].

Application of intuitionistic sets in fields like pattern recognition, HR selection, and medical diagnosis has been recorded. For instance, intuitionistic sets have been implemented in medical diagnostics by De et al. [14], while similarity metrics using IFS were proposed by Liang and Shi [15]. Further, Ejegwa et al. [16] employed intuitionistic sets for career determination, and similarity measures alongside pattern recognition methodologies were presented by Li [17]. Notable works by Szmidt and Kacprzyk [18] and Wei et al. [19] delved into entropy similarity measures and group decision-making using IFS respectively. Jafar et al. [20] undertook a comprehensive exploration of IFSM applications, and Mitchell [21] examined similarity measures in the context of pattern recognition. A more comprehensive framework, the hypersoft set theory, was put forth by Smarandache [22] in 2018 as an extension of soft sets. This new theory adeptly navigates ambiguities, thus enriching decision-making processes. Significant studies on the application of IHSSs have been carried out by Zulqarnain et al. [23], and Yolcu and Ozturk [24] introduced fuzzy hypersoft sets, elucidating their relevance in decision-making. To bolster decision-making, Debnath [25] proposed the weightage operator for fuzzy hypersoft sets, and an extension termed intuitionistic fuzzy hypersoft sets (IFHSS) was presented by Yolcu et al. [26]. The potential of aggregate operators for IFHSS and interval-valued intuitionistic fuzzy hypersoft sets (IVIFHSS) in addressing MCDM problems was explored by Zulqarnain et al. [27, 28]. Other set structures and their applications have also been examined by researchers [29–33].

In the realm of sustainable energy, hydrogen production techniques play a pivotal role. Recognized as a clean and versatile energy source, hydrogen has been explored extensively as a potential solution to challenges posed by greenhouse gas emissions and climate change [34]. Methods for hydrogen production encompass electrolysis, biomass gasification, steam methane reforming (SMR), and solar-powered water splitting. Among these, electrolysis, particularly when powered by renewable sources such as solar and wind, has been identified as the most environmentally advantageous, producing hydrogen devoid of harmful emissions [35]. The inclusion of hydrogen in energy systems has been viewed as instrumental in mitigating dependence on fossil fuels, paving the way for a sustainable energy transition. Thus, emphasis is laid on the reduction of environmental impacts of hydrogen production techniques [36]. Intuitionistic sets have been suggested as valuable tools for addressing challenges in green contexts, especially concerning sustainable energy sources like hydrogen production. Through the harnessing of intuitionistic sets, uncertainties are addressed, MCDM is enhanced, technology selection is optimized, resources are allocated efficiently, and environmental repercussions are assessed, steering the path towards an ecologically sustainable energy future [37].

2 Preliminaries

This section delineates fundamental definitions pivotal to the paper's framework, focusing on Hypersoft Sets (HSS) and IHS's.

2.1 Definition: Hypersoft Set [22]

Let the universal and power set of the universal set be denoted as μ and $P(\mu)$ respectively. Given the sequence $\left(\mathrm{i}^1, \mathrm{i}^2, \mathrm{i}^3, \ldots, \mathrm{i}^n\right)$ where $n \geq 1$ and n represents well-defined attributives, the corresponding attributive elements are arranged in the sequence $\left(\pounds^1, \pounds^2, \pounds^3, \ldots, \pounds^n\right)$. Here, it is required that $\pounds^i \cap \pounds^j = \emptyset$ for all $i \neq j$ with $i, j \in \{1, 2, 3 \ldots n\}$. The pair $(\xi, \pounds)$, under these conditions, is referred to as a hypersoft set, and can be represented as:

$$\xi : \left(\pounds = \pounds^1 \times \pounds^2 \times \pounds^3 \times \ldots \times \pounds^n\right) \rightarrow P(\mu) \tag{1}$$

2.2 Definition: Intuitionistic Hypersoft Set (IHS's) [22, 26]

For the Eq. (1), when values are assigned to each attribute in terms of truthiness, indeterminacy, and falseness such that $\langle \mathrm{t}, \mathrm{f} \rangle$, where $\mathrm{t}, \mathrm{f} : \mu \rightarrow [0, 1]$, and $0 \leq \mathrm{t}(\xi(\varkappa)) + \mathrm{f}(\xi(\varkappa)) \leq 2$, the pair $(\xi, \pounds)$ is then termed an intuitionistic hypersoft set.

2.3 Definition: Single-Valued Intuitionistic Hypersoft Set [22, 26]

For the Eq. (1), when values are assigned to each attribute as

$$\xi : \left(\left(\pounds = \pounds^1 \times \pounds^2 \times \pounds^3 \times \ldots \times \pounds^n\right) \rightarrow \boldsymbol{P}(\boldsymbol{\mu})\right) = \left\{ \begin{array}{c} < \varkappa, .T^i(\xi(\varkappa)) + \boldsymbol{F}^k(\xi(\varkappa)) > .\varkappa \in \boldsymbol{\mu}, \\ \boldsymbol{i}, \boldsymbol{k}. = \mathbf{1}, \mathbf{2}, \mathbf{3}, \ldots, \boldsymbol{n} \end{array} \right\} \text{Also}$$

$$0 \leq \sum_{i=1}^{a} T^i(\xi(\varkappa)) \leq 1, \quad 0 \leq \sum_{k=1}^{c} F^k(\xi(\varkappa)) \leq 1 \tag{2}$$

where, $T^i(\xi(\varkappa)), F^k(\xi(\varkappa)) \subseteq [0, 1]$ are fuzzy numbers and $0 \leq \sum_{i=1}^{a} T^i(\xi(\varkappa)) + \sum_{k=1}^{c} F^k(\xi(\varkappa)) \leq 2$ as represented by (2), the pair $(\xi, \pounds)$ is designated as a single-valued intuitionistic hypersoft set or SVIHS's.

3 Aggregate Operators of IHS's

Complexities arise in decision-making problems due to their multidimensional nature, encompassing multiple attributes or even subsequent subdivisions. Such intricacies have been observed to be beyond the capabilities of the intuitionistic soft set alone. Hence, the need for a novel approach was recognized. In this context, certain aggregate operators have been defined.

3.1 Definition

Let E be the initial universe of discourse and $\mathbf{P}(E)$ is the set of all possibilities of E. Suppose $h_1, h_2, h_3 \ldots\ldots\ldots h_n$ where $n \geq 1$ be n distinct attributes whose corresponding attributive values respectively the sets $H_1, H_2, H_3, \ldots, H_n$ with $H_i \cap H_J = \emptyset, i \neq j$ and $i, j \in \{0, 1, 2, 3 \ldots\ldots\ldots n\}$ then the relation $H_1 \times H_2 \times H_3 \times \ldots\ldots\ldots \times H_n = \alpha$ then the pair (F, α) is said to be Intuitionistic Hypersoft Set (HIS's).

$$F : H_1 \times H_2 \times H_3 \times \ldots\ldots\ldots \times H_n \rightarrow P(E)$$

and

$$F\left(H_1 \times H_2 \times H_3 \times \ldots\ldots\ldots \times H_n\right) = \{< x, \mu(F(\alpha)), \gamma(F(\alpha)) >, x \in E\}$$

where, μ is the value of membership and γ is the value of non-membership such that $\mu : E \rightarrow [0, 1], \gamma : E \rightarrow [0, 1]$ and also $0 < \mu(F(\alpha)) + \gamma(F(\alpha)) < 2$.

3.2 Example

In contemporary, high-velocity professional landscapes, the optimal selection of a laptop has been identified as paramount for those desiring enhanced productivity coupled with seamless mobility. In this particular study, a technologically-oriented consulting firm's approach to determining the ideal laptop for a diverse cadre of remote staff was examined. Criteria and variables employed in this selection process were scrutinized. Among the factors assessed were performance, portability, battery longevity, software compatibility, and fiscal constraints.

This investigation illuminated the intricate interplay between hardware specifications and pragmatic operational needs that underpins such decisions. Consequently, insights are provided that may guide both individuals and entities in navigating the expansive spectrum of laptop options. Let E represent the set of laptops being considered.

$$E = \{e_1, e_2, e_3 \ldots\ldots\ldots e_n\} \tag{3}$$

Also consider the set of attributes:
S_{11}=Laptop type;
S_{12}=Ram capacity;
S_{13}=Screen resolution;
S_{14}=Battery life;
S_{15}=Graphic card;
S_{16}=Processor generation.
And their respective attributes:
S_{11}=Laptop type ={Dell, HP, Samsung, Lenovo};
S_{12}=Ram capacity ={2GB, 4GB, and 8GB};
S_{13}=Screen resolution ={1366 × 768 Pixels, 1920 × 1080 Pixels, 2560 × 1440 Pixels};
S_{14}=Battery life ={4400MAH, 4800MAH, 5200MAH};
S_{15}=Graphic card ={4GB, 8GB, 11GB};
S_{16}=Processor generation ={5th, 6th, 8th}.
Let the function be $F : (S_{11} \times S_{12} \times S_{13} \times S_{14} \times S_{15}) \rightarrow P(E)$.
Intuitionistic Hypersoft Set (IHS's) is defined as:

$$F : (S_{11} \times S_{12} \times S_{13} \times S_{14} \times S_{15}) \rightarrow P(E) \tag{4}$$

Let assume that F {Samsung, 8GB, 1920×1080 Pixels, $4800\text{MAH}, 128$ GB, 6^{th} Generation $\} = \{e_2, e_4\}$.
Then Intuitionistic fuzzy hypersoft set of above assumed relation is:

$$
\begin{aligned}
F(\alpha) = F\Big\{&\text{Samsung, 8 GB, } 1920 \times 1080 \text{ Pixels, 4800 MAH,} \\
&\text{128 GB, } 6^{\text{th}} \text{ Generation}\Big\} \\
= \Big\{ &< e_2(\text{Samsung}\{0.3, 0.1\}, 8GB\{0.9, 0.1\}, 1920 \times 1080 \text{ Pixels} \\
&\{0.1, 0.1\}, 4800MAH\{0.3, 0.2\}, 8GB\{0.7, 0.4\}, \\
&6^{\text{th}} \text{ Generation } \{0.1, 0.6\}) > \\
&< e_4(\text{Samsung}\{0.1, 0.4\}, 128GB\{0.1, 0.3\}, 1920 \times 1080 \text{ Pixels} \\
&\{0.3, 0.1\}, 4800MAH\{0.4, 0.5\}, 8GB\{0.9, 0.1\}, \\
&6^{\text{th}} \text{ Generation } \{0.7, 0.1\}) > \Big\}
\end{aligned} \tag{5}
$$

3.3 Definition: IHS's

Suppose $F(\alpha_1)$ and $F(\alpha_2)$ be two $IHS's$ over E. Suppose $h_1, h_2, h_3 \ldots\ldots\ldots h_n$ where $n \geq 1$ be *n* distinct attributes whose corresponding attributive values respectively the sets $H_1, H_2, H_3 \ldots\ldots\ldots H_n$ with $H_i \cap H_J = \emptyset, i \neq j$ and $i, j \in \{0, 1, 2, 3 \ldots\ldots\ldots n\}$ then the relation $H_1 \times H_2 \times H_3 \times \ldots\ldots\ldots \times H_n = \alpha$ then $F(\alpha_1)$ is the Intuitionistic hypersoft subset of $F(\alpha_2)$ if:

$$
\begin{aligned}
\mu(F(\alpha_1)) \leq \mu(F(\alpha_2)) \\
\gamma(F(\alpha_1)) \geq \gamma(F(\alpha_2))
\end{aligned} \tag{6}
$$

3.4 Definition: Equal IHS$'s$

Suppose $F(\alpha_1)$ and $F(\alpha_2)$ be two $IHS's$ over E. Suppose $h_1, h_2, h_3 \ldots\ldots\ldots h_n$ where $n \geq 1$ be *n* distinct attributes whose corresponding attributive values respectively the sets $H_1, H_2, H_3 \ldots\ldots\ldots H_n$ with $H_i \cap H_J = \emptyset, i \neq j$ and $i, j \epsilon \{0, 1, 2, 3 \ldots\ldots\ldots n\}$ then the relation $H_1 \times H_2 \times H_3 \times \ldots\ldots\ldots \times H_n = \alpha$ then $F(\alpha_1)$ is the $IHS's$ of $F(\alpha_2)$ if:

$$
\begin{aligned}
\mu(F(\alpha_1)) = \mu(F(\alpha_2)) \\
\gamma(F(\alpha_1)) = \gamma(F(\alpha_2))
\end{aligned} \tag{7}
$$

3.5 Definition: Null IHS$'s$

Let $F(\alpha_1)$ be the $IHS's$ over E. Suppose $h_1, h_2, h_3 \ldots\ldots\ldots h_n$ where $n \geq 1$ be *n* distinct attributes whose corresponding attributive values respectively the set $H_1, H_2, H_3 \ldots\ldots\ldots H_n$ with $H_i \cap H_J = \emptyset, i \neq j$ and $i, j \in \{0, 1, 2, 3 \ldots\ldots\ldots n\}$ then the relation $H_1 \times H_2 \times H_3 \times \ldots\ldots\ldots \times H_n = \alpha_1$ then $F(\alpha_1)$ is the null Intuitionistic hypersoft set of if:

$$
\begin{aligned}
\mu(F(\alpha_1)) = 0 \\
\gamma(F(\alpha_1)) = 0
\end{aligned} \tag{8}
$$

3.6 Definition: Compliment of IHS$'s$

Let $F(\alpha_1)$ be the $IHS's$ over E. Suppose $h_1, h_2, h_3 \ldots\ldots\ldots h_n$ where $n \geq 1$ be *n* distinct attributes whose corresponding attributive values respectively the set $H_1, H_2, H_3 \ldots\ldots\ldots H_n$ with $H_i \cap H_J = \emptyset, i \neq j$ and $i, j \in \{0, 1, 2, 3 \ldots\ldots\ldots n\}$ then the relation $H_1 \times H_2 \times H_3 \times \ldots\ldots\ldots \times H_n = \alpha_1$ then $F^c(\alpha_1)$ is the compliment of Intuitionistic fuzzy hypersoft set if:

$$
F^c(\alpha_1) : (\neg H_1 \times \neg H_2 \times \neg H_3 \ldots\ldots \neg H_n) \to F(\alpha_1) \tag{9}
$$

Such that

$$
\begin{aligned}
\mu^c(F(\alpha_1)) = \gamma(F(\alpha_1)) \\
\gamma^c(F(\alpha_1)) = \mu(F(\alpha_2))
\end{aligned} \tag{10}
$$

3.7 Definition: Union of a Two IHS$'s$

Suppose $F(\alpha_1)$ and $F(\alpha_2)$ be two $IHS's$ over E. Suppose $h_1, h_2, h_3 \ldots\ldots\ldots h_n$ where $n \geq 1$ be n distinct attributes whose corresponding attributive values respectively the sets $H_1, H_2, H_3 \ldots\ldots\ldots H_n$ with $H_i \cap H_J = \emptyset, i \neq j$ and $i, j \in \{0, 1, 2, 3 \ldots\ldots\ldots n\}$ then the relation $H_1 \times H_2 \times H_3 \times \ldots\ldots\ldots \times H_n = \alpha$ then $F(\alpha_1) \cup F(\alpha_2)$ is given as:

$$\begin{aligned} \mu(F(\alpha_1) \cup F(\alpha_2)) &= \begin{cases} \mu(F(\alpha_1)) & \text{if } x \in \alpha_1 \\ \mu(F(\alpha_2)) & \text{if } x \in \alpha_2 \\ \max(\mu(F(\alpha_1)), \mu(F(\alpha_2))) & \text{if } x \in \alpha_1 \cap \alpha_2 \end{cases} \\ \gamma(F(\alpha_1) \cup F(\alpha_2)) &= \begin{cases} \gamma(F(\alpha_1)) & \text{if } x \in \alpha_1 \\ \gamma(F(\alpha_2)) & \text{if } x \in \alpha_2 \\ \min(\gamma(F(\alpha_1)), \gamma(F(\alpha_2))) & \text{if } x \in \alpha_1 \cap \alpha_2 \end{cases} \end{aligned} \tag{11}$$

3.8 Definition: Intersection of a Two IHS$'s$

Suppose $F(\alpha_1)$ and $F(\alpha_2)$ be two $IHS's$ over E. Suppose $h_1, h_2, h_3 \ldots\ldots\ldots h_n$ where $n \geq 1$ be n distinct attributes whose corresponding attributive values respectively the sets $H_1, H_2, H_3 \ldots\ldots\ldots H_n$ with $H_i \cap H_J = \emptyset, i \neq j$ and $i, j \in \{0, 1, 2, 3 \ldots\ldots\ldots n\}$ then the relation $H_1 \times H_2 \times H_3 \times \ldots\ldots\ldots \times H_n = \alpha$ then $F(\alpha_1) \cap F(\alpha_2)$ is given as:

$$\begin{aligned} \mu(F(\alpha_1) \cap F(\alpha_2)) &= \begin{cases} \mu(F(\alpha_1)) & \text{if } x \in \alpha_1 \\ \mu(F(\alpha_2)) & \text{if } x \in \alpha_2 \\ \min(\mu(F(\alpha_1)), \mu(F(\alpha_2))) & \text{if } x \in \alpha_1 \cap \alpha_2 \end{cases} \\ \gamma(F(\alpha_1) \cap F(\alpha_2)) &= \begin{cases} \gamma(F(\alpha_1)) & \text{if } x \in \alpha_1 \\ \gamma(F(\alpha_2)) & \text{if } x \in \alpha_2 \\ \max(\gamma(F(\alpha_1)), \gamma(F(\alpha_2))) & \text{if } x \in \alpha_1 \cap \alpha_2 \end{cases} \end{aligned} \tag{12}$$

4 VIKOR Algorithm and Its Application

4.1 The VIKOR Method

The VIKOR Method, a technique within the realm of Multi-Criteria Decision Making (MCDM), was established by Serafim Opricovic in 1979. Within this framework, a compromise solution to conflicting criteria is sought. In the VIKOR process, alternatives are systematically evaluated based on predetermined criteria. Subsequently, they are ranked in a way that ensures the compromise solution closely approximates the ideal solution.

Step 1: Normalize the DM.

Step 2: Weighted DM.

Step 3: Calculation of Ideal Solution (IS).

Step 4: Computation of S_i, R_i, and Q_i.

$$\begin{gathered} S_i = \sum_{j=1}^{n} w_j \frac{(f_j^+ - f_{ij})}{(f_j^+ - f_j^-)}, (i = 1, 2, 3, \ldots .m; j = 1, 2, 3, \ldots .n) \\ R_i = \max_{1 \leq j \leq n} \left[\frac{w_j (f_j^+ - f_{ij})}{(f_j^+ - f_j^-)} \right], (i = 1, 2, 3, \ldots .m; j = 1, 2, 3, \ldots .n) \\ S^* = \min S_i \quad R^* = \min R_i \\ S^+ = \max S_i \quad R^+ = \max R_i \\ Q_i = \frac{V(S_i - S^*)}{(S^+ - S^*)} - \frac{(1 - V)(R_i - R^*)}{(R^+ - R^*)} \end{gathered} \tag{13}$$

where, $V = 0.5$.

Step 5: Final Ranking

To rank the alternative, list the values of S_i, R_i, and Q_i in ascending order.

4.2 Case Study

In the pursuit of identifying the most optimal and cost-effective hydrogen production technology, a comprehensive case study was undertaken. This exhaustive investigation entailed multiple phases, from the selection of diverse alternatives to the meticulous establishment of a coherent criteria system, and subsequent data collection. Eight distinct hydrogen production technologies were rigorously assessed within the confines of this study, with an emphasis placed on their overarching descriptions. Through an extensive review of existing literature in this domain, seven pivotal criteria, spanning both cost and performance dimensions, were delineated. The collated data instrumental to this analysis is encapsulated in Table 1.

Table 1. Statistical overview of hydrogen production technologies up to 2013

Alternatives	Met Hod	E.E CO_2	EE	CC	FOC	VOC	FDC	EAC
		C_1	C_2	C_3	C_4	C_5	C_6	C_7
A_1	SMR	0.080	77.5	172.35	06.48	135.70	128.00	156.02
A_2	CG	0.076	55.8	511.48	25.81	37.550	33.190	104.40
A_3	POX	0.136	67.5	326.60	30.99	191.97	65.320	249.17
A_4	BG	0.020	42.5	262.06	16.71	69.420	44.030	107.16
A_5	PV-EL	0.040	31.2	388.32	16.71	250.66	246.31	298.53
A_6	W-EL	0.005	33.8	388.32	16.71	117.59	112.60	165.46
A_7	H-EL	0.010	52.0	388.32	16.71	92.840	87.970	140.71
A_8	WS-CL	0.012	21.0	857.46	131.67	12.820	11.540	213.29

The weights are calculated using the entropy method. $w1 = 0.2544; w2 = 0.0453; w3 = 0.0620; w4 = 0.2874; w5 = 0.1415; w6 = 0.1703; w7 = 0.0391$.

Step 1: DM is presented in Table 2.

Step 2: Normalization of DM is presented in Table 2.

Table 2. Normalize decision matrix of case study

	C_1	C_2	C_3	C_4	C_5	C_6	C_7
A_1	0.21108	0.20325	0.05231	0.02475	0.14936	0.17559	0.10874
A_2	0.20053	0.14634	0.15523	0.09859	0.04133	0.04553	0.07277
A_3	0.35884	0.17703	0.09912	0.11838	0.21129	0.08961	0.17367
A_4	0.05277	0.11146	0.07954	0.06383	0.07641	0.06040	0.07469
A_5	0.10554	0.08183	0.11785	0.06383	0.27589	0.33789	0.20807
A_6	0.01319	0.08864	0.11785	0.06383	0.12943	0.15447	0.11532
A_7	0.02639	0.13638	0.11785	0.06383	0.10218	0.12068	0.09807
A_8	0.03166	0.05508	0.26024	0.50296	0.01411	0.01583	0.14866

Step 3: Weighted normalization of DM is presented in Table 3.

Table 3. Weighted normalize decision matrix of case study

	C_1	C_2	C_3	C_4	C_5	C_6	C_7
A_1	0.053699	0.0092073	0.0032431	0.0071139	0.021134	0.029903	0.0042519
A_2	0.051014	0.0066293	0.0096245	0.028335	0.0058481	0.0077539	0.0028451
A_3	0.091289	0.0080193	0.0061456	0.034022	0.029898	0.01526	0.0067905
A_4	0.013425	0.0050492	0.0049312	0.018345	0.010812	0.010286	0.0029204
A_5	0.02685	0.0037067	0.007307	0.018345	0.039038	0.057543	0.0081356
A_6	0.0033562	0.0040156	0.007307	0.018345	0.018314	0.026306	0.0045092
A_7	0.0067124	0.0061778	0.007307	0.018345	0.014459	0.020552	0.0038347
A_8	0.0080549	0.0024949	0.016135	0.14455	0.0019966	0.002696	0.0058126

Step 4: Getting the ideal solution,

$$V_j^+ = \begin{bmatrix} 0.091289 & 0.0092073 & 0.0032431 & 0.0071139 & 0.0019966 & 0.002696 & 0.0028451 \end{bmatrix}$$
$$V_j^- = \begin{bmatrix} 0.0033562 & 0.0024949 & 0.016135 & 0.14455 & 0.039038 & 0.057543 & 0.0081356 \end{bmatrix}$$

Step 5: Q_i, S_i and R_i is calculated and presented in Table 4.

Table 4. Q_i, S_i and R_i of case study

$\mathbf{S}_i$	$\mathbf{R}_i$	$\mathbf{Q}_i$
$\mathbf{S}_1$ = **0.2767**	R_1=0.1088	Q_1=0.0506
$\mathbf{S}_2$ = **0.2394**	R_2=0.1165	Q_2=0.0275
$\mathbf{S}_3$ = **0.2530**	R_3=0.1066	Q_3=0.0163
$\mathbf{S}_4$ = **0.3427**	R_4=0.2253	Q_4=0.4518
$\mathbf{S}_5$ = **0.6175**	R_5=0.1864	Q_5=0.6763
$\mathbf{S}_6$ = **0.4804**	R_6=0.2544	Q_6=0.6970
$\mathbf{S}_7$ = **0.4185**	R_7=0.2447	Q_7=0.5961
$\mathbf{S}_8$ = **0.6574**	R_8=0.2874	Q_8=1.0000

S^*=0.2394; R^*=0.1066; S^+=0.6574; R^+=0.287.

Step 6: Order the alternatives, listed by the values Q_i, S_i and R_i.

$\mathbf{S}_i$	$\mathbf{R}_i$	$\mathbf{Q}_i$
$\mathbf{A}_3$	A_3	A_3
$\mathbf{A}_2$	A_1	A_2
$\mathbf{A}_1$	A_2	A_1
$\mathbf{A}_4$	A_5	A_4
$\mathbf{A}_7$	A_4	A_7
$\mathbf{A}_6$	A_7	A_5
$\mathbf{A}_5$	A_6	A_6
$\mathbf{A}_8$	A_8	A_8

In accordance with the specified ranking criteria, alternative A_3 emerges as the optimal choice.

For the evaluation of divergent hydrogen generation technologies, the research integrates the intuitionistic hypersoft set methodology with the VIKOR multi-criteria decision-making approach. This synthesis unveils the merits and limitations of various techniques, both from technical and sustainability viewpoints. By conducting a meticulous analysis, a hierarchical order of the scrutinized methodologies is established, empowering decision-makers with the capability to select premier solutions predicated upon a spectrum of factors, encompassing efficacy, environmental repercussions, and economic feasibility. The research contributes to the evolution of hydrogen production strategies by offering a systematic juxtaposition, facilitating stakeholders to align decisions with sustainability goals and the latest technological advancements.

5 Conclusions

Amidst uncertainties characterizing hydrogen production technologies, the horizon of sustainable energy presents both formidable challenges and potential. The principal objective of this investigation was to discern a solution for the selection from an array of hydrogen generation methodologies. By advocating environmentally benign hydrogen production techniques, the pathway toward a future hallmarked by sustainability and ecological balance is illuminated. Through the amalgamation of the VIKOR Method with the intuitionistic hypersoft set approach, intricate interrelationships between diverse criteria and the evaluated methodologies are comprehensively understood. Stakeholders are endowed with pivotal insights concerning the strengths and weaknesses of each approach from the revelations of the analysis, thus fostering informed decision-making. This research not only augments the domain of eco-friendly hydrogen production but accentuates the imperative of deploying avant-garde decision-making methodologies in grappling with intricate dilemmas pertinent to energy and environmental sustainability. As the urgency for pristine energy sources escalates, the findings of this study stand as a quintessential guidepost for shaping future hydrogen production strategies in more efficacious and sustainable directions.

As the vista unfolds, exploration of contemporary methods such as AHP and TOPSIS within a neutrosophic framework appears promising. Such inquiries hold the potential to broaden understanding and refine decision-making processes. The anticipation is for an era where sustainable energy transitions from an aspirational concept to a palpable reality, reshaping the very essence of our planet through relentless research, innovation, and collaboration.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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