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Assessment Criteria of Solar Hydrogen Production Plant Based on Fuzzy Multi-Criteria Decision-Making Methodology

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Abstract: This study presents a comprehensive solar hydrogen production plant assessment, focusing on evaluating its technological efficiency, economic viability, environmental impact, and operational reliability. Leveraging solar photovoltaic technology and electrolysis processes, the plant converts abundant solar energy into hydrogen, offering a sustainable pathway towards clean energy production. The assessment encompasses a detailed analysis of solar panel efficiency, electrolyze performance, cost-effectiveness, lifecycle emissions, and operational considerations. Findings reveal that while technological advancements drive enhanced efficiency and reliability, economic viability remains challenging due to high initial capital costs. However, the environmental benefits, including reduced carbon footprint and water usage, underscore the plant's potential contribution to a low-carbon future. Operational assessments highlight the need for scalable, grid-integrated systems with robust safety measures. Overall, the evaluation provides critical insights into the opportunities and challenges of solar-driven hydrogen production, offering recommendations to optimize plant efficiency, reduce costs, and promote its widespread adoption. We used the multi-criteria decision-making (MCDM) concept for various criteria. The SWARA method is used to compute the weights of criteria. The SWARA method is integrated with fuzzy numbers to overcome the uncertainty data. The main results show that solar production has the highest rank.

Keywords: Fuzzy Sets; Solar; Hydrogen Production; MCDM; Assessment; SWARA Method.

1. Introduction

Solar hydrogen production is a beacon of innovation in the quest for sustainable energy solutions, offering a promising avenue towards clean, renewable fuel generation. As the world grapples with the urgency of climate change and seeks to transition away from fossil fuel dependence, integrating solar energy for hydrogen production emerges as a compelling frontier in pursuing a carbon-neutral energy landscape. At the core of this transformative endeavor lie solar hydrogen production plants, leveraging solar photovoltaic (PV) technology and electrolysis processes to convert abundant solar energy into hydrogen, a versatile and environmentally friendly energy carrier. The potential of solar hydrogen production plants to facilitate the decarbonization of energy systems, enable energy storage, and drive the emergence of a hydrogen-based economy underscores their significance in the sustainable energy paradigm[1]–[3].

Assessing the viability and efficiency of solar hydrogen production plants demands a multifaceted evaluation encompassing technological, economic, environmental, and operational aspects. These assessments are pivotal in determining the effectiveness and feasibility of such facilities and shaping strategies for scalability, cost-effectiveness, and widespread adoption. The technological assessment delves into the efficiency of these plants' solar panels, electrolyzes, and storage systems. Evaluating the performance of these components in converting solar energy into hydrogen, alongside advancements in materials, designs, and system integration, holds the key to enhancing overall plant efficiency and output[4]–[6].

Moreover, economic assessments are imperative to gauge solar hydrogen production's cost competitiveness and financial viability. Analyses of capital expenditures, operational costs, hydrogen production costs, and potential revenue streams play a pivotal role in determining these facilities' economic feasibility and attractiveness. Environmental assessments are integral to the evaluation, focusing on the lifecycle emissions, environmental impacts, and sustainability credentials of solar hydrogen production. Understanding the ecological footprint, including water usage, waste generation, and emissions, is crucial in ensuring these plants align with sustainability goals. Operational assessments encompass plant reliability, grid integration, scalability, and safety considerations, contributing to solar hydrogen production plants' overall reliability and functionality[7]–[9].

1.2 Renewable Energy

The global pursuit of sustainable energy solutions has spurred a monumental shift in how societies harness and perceive power generation. At the heart of this transformation lies the ascent of renewable energy sources, marking a pivotal departure from traditional fossil fuel-centric models toward a cleaner, more sustainable energy landscape[10], [11]. Renewable energy, often termed the "energy of the future," refers to energy derived from naturally replenishing resources, notably solar, wind, hydroelectric, geothermal, and biomass sources. Unlike finite fossil fuels, these sources offer an abundant and inexhaustible energy supply, offering a promising avenue to address the dual challenges of climate change mitigation and energy security[12], [13].

The evolution of renewable energy is a testament to human ingenuity and technological advancements. Over the past few decades, breakthroughs in solar photovoltaic (PV) technology, wind turbine efficiency, and energy storage solutions have propelled renewable energy to the forefront of the global energy agenda. Consequently, the cost competitiveness of renewables has improved dramatically, making them increasingly viable alternatives to conventional power sources. The imperatives driving the adoption of renewable energy are manifold. Chief among them is the urgent need to mitigate the adverse impacts of climate change[14], [15]. The combustion of fossil fuels releases greenhouse gases, contributing significantly to global warming and environmental degradation. In contrast, renewable energy sources offer a carbon-neutral or low-carbon footprint, presenting a tangible solution to curb emissions and combat climate change[16], [17].

Moreover, renewable energy offers a decentralized and democratized approach to energy access. It empowers communities, industries, and nations to harness local resources, fostering energy independence and resilience. This energy production and distribution democratization is reshaping traditional power dynamics and promoting economic development opportunities across regions[18], [19].

The journey towards a renewable energy future is both a global imperative and a collective responsibility. Governments, industries, innovators, and citizens worldwide are increasingly investing in and advocating for renewable energy adoption. This paradigm shift redefines the energy landscape and heralds a sustainable future built on innovation, resilience, and environmental stewardship[18], [20], [21].

2. Proposed Methodology

In this section, we introduced some mathematical equations in the fuzzy sets and the steps of the SWARA method.

Let two triangular fuzzy numbers as $X_1 = (a_1, b_1, c_1)\ and\ X_2 = (a_2, b_2, c_2)$

Fuzzy Summation

$$X_1 \oplus X_2 = (a_1 + a_2, b_1 + b_2, c_1 + c_2) \quad (1)$$

Fuzzy subtract

$$X_1 - X_2 = (a_1 - c_2, b_1 - b_2, c_1 - a_2) \quad (2)$$

$$X_1 \otimes X_2 = (a_1 a_2, b_1 b_2, c_1 c_2) \quad (3)$$

$$X_1 \div X_2 = (a_1/c_2, b_1/b_2, c_1/a_2) \quad (4)$$

In 2010, the Step-wise Weight Assessment Ratio Analysis (SWARA) was created. The primary source of competency with the SWARA approach is specialists. Its main advantage is SWARA's capacity to assess expert views and calculate the relative relevance ratio for every criterion[22]–[24]. When using the SWARA approach instead of other MCDM techniques, experts use their implicit expertise, abilities, and data more effectively. The requirements significance is often assessed using prioritization weights from a pairwise contrast matrix. Experts may freely set criteria in the SWARA technique without using an assessment scale[25]–[27].

2.1 Arrange the criteria with the highest importance.

The requirements are ranked according to expert opinion, with the most significant factors coming first and the least essential ones coming last. Since real-world issue solving is uncertain, professionals are given greater latitude using the linguistic scale. To find out what experts think about the variables, the scale of linguistics is represented as a triangular fuzzy number.

2.2 Assign the linguistic scale to all criteria.

The second requirement is where the procedure begins, with the experts assigning a linguistic variable for every criterion j depending on how vital the preceding (j − 1) criterion was about each other. The relative significance of the average value is the name given to this ratio.

2.3 Calculate the fuzzy coefficient.

$$y_j = \begin{cases} 1 & j = 1 \\ S_{j+1} & j > 1 \end{cases} \quad (5)$$

2.4 Compute the fuzzy weight.

$$u_j = \begin{cases} 1 & j = 1 \\ \frac{u_{i+1}}{y_j} & j > 1 \end{cases} \quad (6)$$

2.5 Compute the relative fuzzy weight.

$$w_j = \frac{u_j}{\sum_{k=1}^{n} u_k} \quad (7)$$

3. Application

We proposed an application with 15 criteria to evaluate solar hydrogen production by the fuzzy SWARA method.

We used 15 criteria as[28]–[31]:

A. Solar Resource Assessment: Analyze solar irradiance and availability at the plant location to determine solar panels' feasibility and potential output.

B. Electrolyzer Efficiency: Select high-efficiency electrolyzers capable of efficiently converting solar energy to hydrogen.

C. System Scalability: Design the plant to be scalable, allowing for expansion or contraction based on demand or available solar resources.

D. Storage Solutions: Implement effective hydrogen storage systems that maintain the gas under safe conditions, considering factors like pressure vessels or chemical storage options.

E. Electrical Grid Integration: Ensure compatibility with the electrical grid, enabling efficient transmission of excess or power reception during low solar availability.

F. Hydrogen Purity and Quality Control: Establish measures to maintain high hydrogen purity and quality during production, storage, and distribution.

G. Safety Measures: Implement safety protocols to prevent accidents, including gas leakage detection, emergency shutdown systems, and adherence to safety standards.

H. Environmental Impact: Minimize ecological impact by assessing the lifecycle emissions and ensuring responsible disposal or recycling of byproducts.

I. Cost Consideration: Balance initial investment costs with long-term operational costs to ensure economic viability and competitiveness.

J. Water Usage and Recycling: Develop strategies to optimize water usage in electrolysis and consider water recycling methods to reduce consumption.

K. Remote Monitoring and Control: Implement remote monitoring and control systems for efficient operation, maintenance, and troubleshooting.

L. Regulatory Compliance: Ensure compliance with local regulations, safety standards, and environmental regulations governing hydrogen production and storage.

M. Maintenance and Durability: Use durable components and establish regular maintenance schedules to ensure system longevity and efficiency.

N. Grid Stability: Consider the impact of intermittent solar power on grid stability and implement measures to mitigate fluctuations.

O. Hydrogen Distribution and Infrastructure: Plan for the distribution of hydrogen, including transportation, storage, and potential integration into existing infrastructure.

3.1 Build the comparison matrix between criteria by the fuzzy numbers, then we built it by the crisp values as shown in Tables 1 and 2.

Table 1. The comparison matrix by the fuzzy numbers.

	SPC1	SPC2	SPC3	SPC4	SPC5	SPC6	SPC7	SPC8	SPC9	SPC10	SPC11	SPC12	SPC13	SPC14	SPC15
SPC1	1	(0.1,0.3,0.5)	(0.0,0.1,0.3)	(0.5,0.7,0.9)	(0.1,0.3,0.5)	(0.0,0.1,0.3)	(0.1,0.3,0.5)	(0.3,0.5,0.7)	(0.0,0.1,0.3)	(0.5,0.7,0.9)	(0.1,0.3,0.5)	(0.0,0.1,0.3)	(0.5,0.7,0.9)	(0.5,0.7,0.9)	(0.0,0.1,0.3)
SPC2	1/(0.1,0.3,0.5)	1	(0.1,0.3,0.5)	(0.7,0.9,1)	(0.7,0.9,1)	(0.7,0.9,1)	(0.7,0.9,1)	(0.7,0.9,1)	(0.3,0.5,0.7)	(0.7,0.9,1)	(0.5,0.7,0.9)	(0.7,0.9,1)	(0.1,0.3,0.5)	(0.7,0.9,1)	(0.1,0.3,0.5)
SPC3	1/(0.0,0.1,0.3)	1/(0.1,0.3,0.5)	1	(0.5,0.7,0.9)	(0.7,0.9,1)	(0.9,1,1)	(0.1,0.3,0.5)	(0.9,1,1)	(0.9,1,1)	(0.7,0.9,1)	(0.1,0.3,0.5)	(0.7,0.9,1)	(0.9,1,1)	(0.5,0.7,0.9)	(0.0,0.1,0.3)
SPC4	1/(0.5,0.7,0.9)	1/(0.7,0.9,1)	1/(0.5,0.7,0.9)	1	(0.1,0.3,0.5)	(0.9,1,1)	(0.9,1,1)	(0.9,1,1)	(0.1,0.3,0.5)	(0.9,1,1)	(0.9,1,1)	(0.9,1,1)	(0.5,0.7,0.9)	(0.5,0.7,0.9)	(0.3,0.5,0.7)
SPC5	1/(0.1,0.3,0.5)	1/(0.7,0.9,1)	1/(0.7,0.9,1)	1/(0.1,0.3,0.5)	1	(0.5,0.7,0.9)	(0.9,1,1)	(0.9,1,1)	(0.9,1,1)	(0.7,0.9,1)	(0.1,0.3,0.5)	(0.5,0.7,0.9)	(0.1,0.3,0.5)	(0.9,1,1)	(0.7,0.9,1)
SPC6	1/(0.0,0.1,0.3)	1/(0.7,0.9,1)	1/(0.9,1,1)	1/(0.9,1,1)	1/(0.5,0.7,0.9)	1	(0.1,0.3,0.5)	(0.7,0.9,1)	(0.9,1,1)	(0.7,0.9,1)	(0.5,0.7,0.9)	(0.7,0.9,1)	(0.9,1,1)	(0.7,0.9,1)	(0.0,0.1,0.3)
SPC7	1/(0.1,0.3,0.5)	1/(0.7,0.9,1)	1/(0.1,0.3,0.5)	1/(0.9,1,1)	1/(0.9,1,1)	1/(0.1,0.3,0.5)	1	(0.1,0.3,0.5)	(0.5,0.7,0.9)	(0.7,0.9,1)	(0.9,1,1)	(0.9,1,1)	(0.7,0.9,1)	(0.9,1,1)	(0.7,0.9,1)
SPC8	1/(0.3,0.5,0.7)	1/(0.7,0.9,1)	1/(0.9,1,1)	1/(0.9,1,1)	1/(0.9,1,1)	1/(0.7,0.9,1)	1/(0.1,0.3,0.5)	1	(0.3,0.5,0.7)	(0.7,0.9,1)	(0.5,0.7,0.9)	(0.5,0.7,0.9)	(0.5,0.7,0.9)	(0.7,0.9,1)	(0.7,0.9,1)
SPC9	1/(0.0,0.1,0.3)	1/(0.3,0.5,0.7)	1/(0.9,1,1)	1/(0.1,0.3,0.5)	1/(0.9,1,1)	1/(0.9,1,1)	1/(0.5,0.7,0.9)	1/(0.3,0.5,0.7)	1	(0.3,0.5,0.7)	(0.5,0.7,0.9)	(0.7,0.9,1)	(0.5,0.7,0.9)	(0.7,0.9,1)	(0.0,0.1,0.3)
SPC10	1/(0.5,0.7,0.9)	1/(0.7,0.9,1)	1/(0.7,0.9,1)	1/(0.9,1,1)	1/(0.7,0.9,1)	1/(0.7,0.9,1)	1/(0.7,0.9,1)	1/(0.7,0.9,1)	1/(0.3,0.5,0.7)	1	(0.1,0.3,0.5)	(0.7,0.9,1)	(0.7,0.9,1)	(0.5,0.7,0.9)	(0.7,0.9,1)
SPC11	1/(0.1,0.3,0.5)	1/(0.5,0.7,0.9)	1/(0.1,0.3,0.5)	1/(0.9,1,1)	1/(0.1,0.3,0.5)	1/(0.5,0.7,0.9)	1/(0.9,1,1)	1/(0.5,0.7,0.9)	1/(0.5,0.7,0.9)	1/(0.1,0.3,0.5)	1	(0.3,0.5,0.7)	(0.5,0.7,0.9)	(0.7,0.9,1)	(0.5,0.7,0.9)
SPC12	1/(0.0,0.1,0.3)	1/(0.7,0.9,1)	1/(0.7,0.9,1)	1/(0.9,1,1)	1/(0.5,0.7,0.9)	1/(0.7,0.9,1)	1/(0.9,1,1)	1/(0.5,0.7,0.9)	1/(0.7,0.9,1)	1/(0.7,0.9,1)	1/(0.3,0.5,0.7)	1	(0.1,0.3,0.5)	(0.7,0.9,1)	(0.0,0.1,0.3)
SPC13	1/(0.5,0.7,0.9)	1/(0.1,0.3,0.5)	1/(0.9,1,1)	1/(0.5,0.7,0.9)	1/(0.1,0.3,0.5)	1/(0.9,1,1)	1/(0.7,0.9,1)	1/(0.5,0.7,0.9)	1/(0.5,0.7,0.9)	1/(0.7,0.9,1)	1/(0.5,0.7,0.9)	(0.1,0.3,0.51/)	1	(0.5,0.7,0.9)	(0.3,0.5,0.7)
	SPC1	SPC2	SPC3	SPC4	SPC5	SPC6	SPC7	SPC8	SPC9	SPC10	SPC11	SPC12	SPC13	SPC14	SPC15
SPC1	1	(0.1,0.3,0.5)	(0.0,0.1,0.3)	(0.5,0.7,0.9)	(0.1,0.3,0.5)	(0.0,0.1,0.3)	(0.1,0.3,0.5)	(0.3,0.5,0.7)	(0.0,0.1,0.3)	(0.5,0.7,0.9)	(0.1,0.3,0.5)	(0.0,0.1,0.3)	(0.5,0.7,0.9)	(0.5,0.7,0.9)	(0.0,0.1,0.3)

Table 2. The comparison matrix by the crisp values.

	SPC1	SPC2	SPC3	SPC4	SPC5	SPC6	SPC7	SPC8	SPC9	SPC10	SPC11	SPC12	SPC13	SPC14	SPC15
SPC1	1	0.3	0.1333	0.7	0.3	0.1333	0.3	0.5	0.1333	0.7	0.3	0.1333	0.7	0.7	0.1333
SPC2	3.3333	1	0.3	0.8667	0.8667	0.8667	0.8667	0.8667	0.5	0.8667	0.7	0.8667	0.3	0.8667	0.3
SPC3	7.5019	3.3333	1	0.7	0.8667	0.9667	0.3	0.9667	0.9667	0.8667	0.3	0.8667	0.9667	0.7	0.1333
SPC4	1.4286	1.1538	1.4286	1	0.3	0.9667	0.9667	0.9667	0.3	0.9667	0.9667	0.9667	0.7	0.7	0.5
SPC5	3.3333	1.1538	1.1538	3.3333	1	0.7	0.9667	0.9667	0.9667	0.8667	0.3	0.7	0.3	0.9667	0.8667
SPC6	7.5019	1.1538	1.0345	1.0345	1.4286	1	0.3	0.8667	0.9667	0.8667	0.7	0.8667	0.9667	0.8667	0.1333
SPC7	3.3333	1.1538	3.3333	1.0345	1.0345	3.3333	1	0.3	0.7	0.8667	0.9667	0.9667	0.8667	0.9667	0.8667
SPC8	2	1.1538	1.0345	1.0345	1.0345	1.1538	3.3333	1	0.5	0.8667	0.7	0.7	0.7	0.8667	0.8667
SPC9	7.5019	2	1.0345	3.3333	1.0345	1.0345	1.4286	2	1	0.5	0.7	0.8667	0.7	0.8667	0.1333
SPC10	1.4286	1.1538	1.1538	1.0345	1.1538	1.1538	1.1538	1.1538	2	1	0.3	0.8667	0.8667	0.7	0.8667
SPC11	3.3333	1.4286	3.3333	1.0345	3.3333	1.4286	1.0345	1.4286	1.4286	3.3333	1	0.5	0.7	0.8667	0.7
SPC12	7.5019	1.1538	1.1538	1.0345	1.4286	1.1538	1.0345	1.4286	1.1538	1.1538	2	1	0.3	0.8667	0.1333
SPC13	1.4286	3.3333	1.0345	1.4286	3.3333	1.0345	1.1538	1.4286	1.4286	1.1538	1.4286	3.3333	1	0.7	0.5
SPC14	1.4286	1.1538	1.4286	1.4286	1.0345	1.1538	1.0345	1.1538	1.1538	1.4286	1.1538	1.1538	1.4286	1	0.1333
SPC15	7.5019	3.3333	7.5019	2	1.1538	7.5019	1.1538	1.1538	7.5019	1.1538	1.4286	7.5019	2	7.5019	1

3.2 Assign the linguistic scale to all criteria.

3.3 Calculate the fuzzy coefficient by Eq. (5)

3.4 Compute the fuzzy weight by Eq. (6)

3.5 Compute the relative fuzzy weight by Eq. (7) as shown in Figure 1. The solar resource criterion is the highest weight and hydrogen distribution is the least weight.

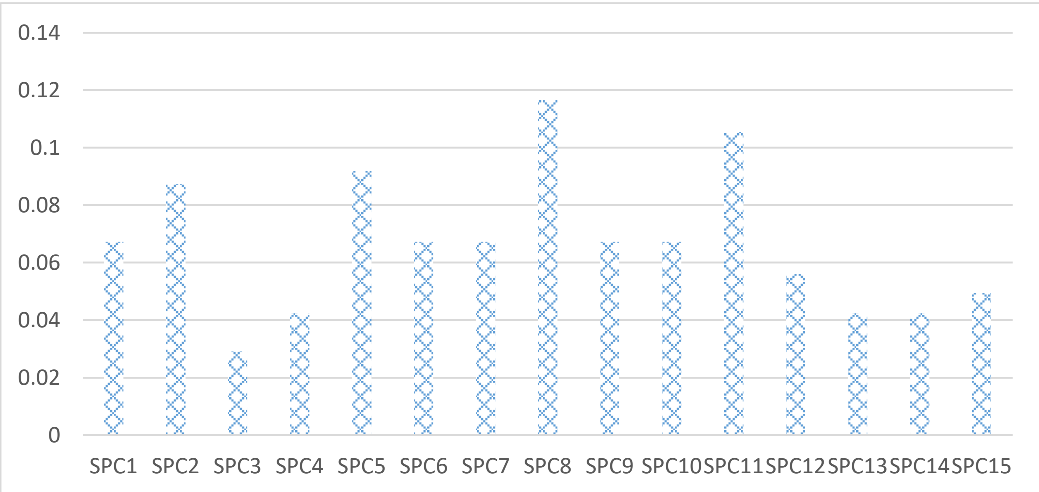

Figure 1. The weights of criteria.

4. Conclusions

The solar hydrogen production plant assessment has illuminated its promise and the hurdles to its widespread adoption. Technologically, advancements in solar panel efficiency and electrolyzer performance exhibit a positive trajectory toward higher output and reliability. However, economic viability remains a significant barrier due to substantial initial investment costs. To surmount this challenge, strategic interventions in research and development, alongside policy incentives, are imperative to drive down costs and improve cost-effectiveness. Despite economic constraints, the environmental benefits are substantial, with reduced carbon emissions and minimized water usage, underscoring the plant's pivotal role in a sustainable energy landscape. Operationally, scalability, grid integration, and stringent safety protocols emerge as critical areas for improvement. The assessment emphasizes the need for holistic approaches integrating technological innovation, economic feasibility, environmental stewardship, and operational reliability to propel the solar hydrogen production industry forward. Addressing these facets and implementing strategic recommendations make the path to a sustainable and scalable solar-driven hydrogen economy clearer, paving the way for a future powered by clean and renewable energy sources. We used the MCDM concept to deal with various criteria. The SWARA method is used to compute the weights of criteria. The SWARA is integrated with the fuzzy sets to deal with vague data. The results show that solar production has the highest rank.

Author Contributions

All authors contributed equally to this work.

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Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

Conflicts of Interest

The authors declare that there is no conflict of interest in the research.

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