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Analyzing The Roadblocks of Green Hydrogen Energy Deployment: DEMATEL-Based Approach

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Abstract. In the present era, carbon emissions are experiencing a global upsurge. The greenhouse gas emissions are required to be brought down to net zero levels to attain environmental sustainability, with more reliance on renewable energy sources. To attain this, the role of green hydrogen generation becomes relevant in the realm of renewable energy. However, the storage and logistics of green hydrogen are complex and are inhibited by several challenges. This study systematically examines the interrelationships and influences among various roadblocks faced by the green hydrogen sector and offers a comprehensive analysis of the complex relationships between the key challenges by utilizing the DEMATEL (Decision-Making Trial and Evaluation Laboratory) approach. The findings contribute to a deeper understanding of the multifaceted barriers and provide a structured framework for policymakers, researchers, and industry stakeholders.

1 Introduction

Amidst the challenges posed by climate change, the global requirement to transition towards cleaner and more sustainable energy sources has become increasingly urgent [1]. The recent United Nations Climate Change Conference of the Parties (COP 26) reinvigorated pledges to eliminate coal usage and attain a state of net-zero emissions by the year 2050 [2]. Renewable energy sources present a remarkable opportunity for both environmental and economic advancement, distinct from the limitations associated with fossil fuels, which are finite and non-renewable in nature [3]–[5]. The utilization of renewable energy holds the potential to address the world's energy needs sustainably, owing to its abundant and replenishing nature. Moreover, the adoption of renewable energy sources offers a significant avenue for effectively mitigating the challenges of global warming and climate change, as their utilization generates significantly lower greenhouse gas emissions compared to traditional fossil fuel-based energy production [6]. This dual benefit of meeting energy demands while concurrently contributing to climate resilience underscores the imperative role that renewable energy sources play in shaping a sustainable and environmentally responsible energy landscape [7]. Hydrogen, a clean energy source, has garnered substantial attention as an increasingly prominent alternative to fossil fuels. This interest stems from its potential as a versatile fuel serving as an energy carrier, and a medium for energy storage in cells [8]. Green hydrogen, produced through the electrolysis of water using renewable energy sources,

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represents a versatile and clean energy carrier that has the potential to revolutionize various sectors, ranging from transportation to industrial processes.

However, the adoption of green hydrogen technology faces numerous challenges that require thorough examination. These challenges are technological, economic, policy, and social in nature, necessitating a careful analysis of their interconnections. To navigate these intricacies effectively, there is a critical need for robust analytical frameworks that can provide insights into the causal relationships among these challenges and support strategic decision-making. This research article presents a comprehensive analysis of the roadblocks hindering the successful deployment of green hydrogen energy, employing a DEMATEL-based approach. This approach allows us to systematically explore the intricate web of barriers by unraveling the mutual influences and dependencies among them. By providing a structured and quantifiable methodology, this research aims to enhance the understanding of the complexities surrounding green hydrogen adoption and facilitate the development of targeted interventions and strategies.

2 Literature Background

Hydrogen is envisioned as the future's premier energy carrier due to its capacity to effectively tackle numerous pressing energy and sustainability challenges that both industries and the global economies currently confront [9], [10]. The proportion of green hydrogen is poised to experience a substantial and rapid increase, potentially leading to a significant contribution of over 24% to meet global energy demands by the year 2050. Green Hydrogen can be generated through various methods, including renewable sources, nuclear energy, or even fossil fuels in conjunction with carbon capture, utilization, and storage (CCUS) technologies and the emissions associated with its production can vary significantly, ranging from as low as 43 gCO2e/kg to 9.3 kgCO2e/kg of hydrogen [11]. In the production of green hydrogen, the electrolysis of water involves the conversion of electricity into chemical substances, specifically hydrogen and oxygen [12], [13].

The predominant method for hydrogen production is Steam Methane Reforming (SMR) and a substantial portion of hydrogen generation, approximately 82% of the total production (equivalent to 94 million tons in 2021), stems directly from sources such as methane, oil, and carbon-based feedstocks while 0.04% is from renewable electricity [14].

2.1 Barriers to Green Hydrogen Deployment

The following are the barriers associated with the hydrogen energy sectoral development. The barriers are generally classified as production, storage, transportation, and end-use barriers [15]. However, in the present study, only the barriers related to the production and storage of green hydrogen are considered in totality.

2.1.1 Production System Inefficiencies (PSI)

In the electrolytic method of hydrogen production, water is split using electricity. Further, steam reforming is used to produce hydrogen from biomass, methane, and so forth. These production systems have a low efficiency and, thus are one of the challenges toward green hydrogen production.

2.1.2 High Cost of Production (HCP)

Producing green hydrogen through electrolysis is presently more costly than hydrogen generated from fossil fuels. The high cost is due to the expenses of renewable energy sources, electrolysis equipment, and infrastructure. As a result, making green hydrogen competitive in cost with other forms of hydrogen is a major challenge.

2.1.3 Limited Availability of Compressors (LAC)

Hydrogen, produced through electrolysis, needs to be efficiently compressed to high pressures (often exceeding 350 bar or 5,000 psi) for storage, transport, and utilization. The scarcity of suitable hydrogen compressors and associated infrastructure can hinder the entire hydrogen supply chain.

2.1.4 Complex Steam Reforming (CSR)

Biomass-derived liquids, such as bio-oils or pyrolysis oils, contain a wide variety of organic compounds, including carbohydrates, lignin-derived compounds, fats, and oils. These compounds often have larger and more intricate molecular structures compared to the relatively simpler hydrocarbons found in fossil fuels like natural gas or diesel, resulting in a high complexity of the steam reforming processes.

2.1.5 Adaptability to different compositions (ADC)

Efficient hydrogen production from renewable and biomass-derived feedstocks requires reformers that can adapt to varying compositions, flow rates, and local heat sources. The ability to handle different types of feedstocks and adjust to changing operating conditions is crucial for producing hydrogen efficiently. Reformers must also be able to handle impurities in the feedstock, incorporate the right design of the catalyst bed, and use heat exchangers for efficient heat transfer.

2.1.6 Scaling up of Microbial Electrolysis Cells (MEC)

In the fermentation process for hydrogen production from sugar-rich biomass, microorganisms are employed through microbial electrolysis cells (MECs). While this approach holds great promise for sustainable hydrogen production, scaling up MEC systems from laboratory or pilot-scale to industrial or commercial levels is a complex task. It involves considerations of reactor design, electrode materials, and system engineering, among other factors.

2.1.7 Low Durability of Storage Materials (DSM)

The limited resilience of materials (such as fibers, metals, polymers, etc.) employed in hydrogen storage, coupled with the potential for chemical interactions with the generated hydrogen, gives rise to safety apprehensions

2.1.8 Lack of Flow Control Systems (LFC)

Lack of flow control system is another challenge. When the precision in regulating hydrogen flow at refueling stations is insufficient, it can have a significant impact on the system's evaporation and loss. This can lead to decreased efficiency and increased expenses in the long run.

3 Decision Approach

The authors of this study have opted for a multi-criteria decision-making (MCDM) approach to address the complex relationships of interrelated factors. Among various MCDM tools, they have utilized the Decision Making Trial and Evaluation Laboratory (DEMATEL) methodology, which is deemed the most suitable solution. This decision was made due to DEMATEL's ability to analyze dependencies among factors while overcoming constraints related to sample size [16]. DEMATEL provides a comprehensive framework for evaluating a structural model that involves causal interactions among involved barriers [17]. By utilizing an influence map, it allows for the analysis of interconnected clusters of issues [18].

DEMATEL has been widely used in various fields due to its effectiveness in exploring relationships among factors. Its applications include operations research [19], decision-making in e-waste management [20], and enhancing supply chain resilience [21]. Therefore, the authors' decision to employ DEMATEL in this study is based on its ability to delve into causal relationships among the barriers to deploying green hydrogen.

The steps of DEMATEL are given below:

Step 1: Experts were invited to contribute to the data collection process by assessing the impact of each element i on every other element j, indicated by a_{ij} on a scale from 0 (No influence) to 4 (very high influence). Based on these assessments, a direct relations matrix $\boldsymbol{A}$ was generated. This matrix $\boldsymbol{A}$ serves as a tool for visualizing pairwise comparisons of causal relationships. For systems influenced by 'n' variables, the association matrix $\boldsymbol{A}$ is represented as shown in Eq (1).

$$\boldsymbol{A} = \begin{bmatrix} 0 & a_{12} & \cdots & a_{1n} \\ a_{21} & 0 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 0 \end{bmatrix} \tag{1}$$

Step 2: The normalization is carried out using equations (2) & (3).

$$\boldsymbol{N} = \boldsymbol{A}/p \tag{2}$$

$$p = max_{1 \le i \le n}\left\{\sum_{j=1}^{n} a_{ij}\right\} \tag{3}$$

Step 3: The total relation matrix $\boldsymbol{T}$ is obtained from $\boldsymbol{N}$, using equation (4) where $\boldsymbol{I}$ represents the identity matrix.

$$\boldsymbol{T} = \boldsymbol{N}(\boldsymbol{I} - \boldsymbol{N})^{-1} \tag{4}$$

Step 4: Matrices $\boldsymbol{D}$ and $\boldsymbol{R}$ are obtained from the row and column sums.

$$\boldsymbol{D} = \left[\sum_{j=1}^{n} m_{ij}\right]_{n\times 1} = (r_1, r_2, \dots, r_i, \dots, r_n) \tag{5}$$

$$\boldsymbol{R} = \left[\sum_{i=1}^{n} m_{ij}\right]_{1\times n}' = (s_1, s_2, \dots, s_i, \dots, s_n) \tag{6}$$

$$\boldsymbol{T} = m_{ij} \quad i, j = 1,2,3, \dots n$$

Step 5: The data set of $\{r_i + s_i, r_i - s_i\}$ are plotted using $(r_i + s_i)$ as the horizontal axis and $(r_i - s_i)$ as the vertical axis.

4 Analysis

A group of ten experts, each with an average of fifteen years of experience, were asked to share their viewpoints on how the identified eight factors are causally connected. They used the scale described in Step 1 to provide their evaluations. Table 1 shows the direct relation matrix that resulted from combining all of the experts' responses.

Table 1. Direct Relations Matrix

	DSM	LAC	CSR	HCP	MEC	ADC	LFC	PSI
DSM	0.000	1.100	1.600	1.400	1.700	0.300	1.200	1.400
LAC	0.000	0.000	0.700	2.200	0.400	0.400	0.600	1.400
CSR	0.000	0.000	0.000	2.400	0.600	0.600	0.400	1.600
HCP	0.000	1.300	1.900	0.000	1.700	0.500	1.900	2.200
MEC	0.000	0.700	1.300	1.900	0.000	0.100	2.000	1.400
ADC	0.000	1.400	1.600	1.800	1.100	0.000	1.800	2.100
LFC	0.000	0.600	1.400	1.900	1.900	0.000	0.000	1.800
PSI	0.000	0.000	0.900	1.600	1.400	0.500	0.900	0.000

The normalization of Direct relation matrix is done using equations (2) and (3) and is given in Table 2.

Table 2. Normalized Matrix

	DSM	LAC	CSR	HCP	MEC	ADC	LFC	PSI
DSM	0.000	0.112	0.163	0.143	0.173	0.031	0.122	0.143
LAC	0.000	0.000	0.071	0.224	0.041	0.041	0.061	0.143
CSR	0.000	0.000	0.000	0.245	0.061	0.061	0.041	0.163
HCP	0.000	0.133	0.194	0.000	0.173	0.051	0.194	0.224
MEC	0.000	0.071	0.133	0.194	0.000	0.010	0.204	0.143
ADC	0.000	0.143	0.163	0.184	0.112	0.000	0.184	0.214
LFC	0.000	0.061	0.143	0.194	0.194	0.000	0.000	0.184
PSI	0.000	0.000	0.092	0.163	0.143	0.051	0.092	0.000

The Total relation matrix is shown in Table 3.

Table 3. Total Relations Matrix

	DSM	LAC	CSR	HCP	MEC	ADC	LFC	PSI
DSM	0.000	0.288	0.531	0.660	0.530	0.145	0.481	0.614
LAC	0.000	0.133	0.339	0.558	0.307	0.123	0.320	0.472
CSR	0.000	0.139	0.278	0.575	0.330	0.142	0.311	0.492
HCP	0.000	0.305	0.569	0.566	0.546	0.169	0.553	0.704
MEC	0.000	0.225	0.454	0.627	0.334	0.111	0.497	0.553
ADC	0.000	0.334	0.572	0.754	0.522	0.130	0.571	0.732
LFC	0.000	0.216	0.465	0.632	0.501	0.105	0.330	0.587
PSI	0.000	0.131	0.347	0.495	0.382	0.124	0.341	0.330

The impacts given and taken by each factor were calculated using equations (5) and (6) and are explained in Table 4.

Table 4. Relationships among barriers

	d	r	d+r	d-r
DSM	3.248816	0	3.248816	3.248816
LAC	2.251893	1.770678	4.022572	2.251893
CSR	2.266339	3.5562	5.822539	2.266339
HCP	3.410506	4.868499	8.279005	3.410506
MEC	2.800805	3.450397	6.251202	2.800805
ADC	3.614364	1.047235	4.6616	2.567129
LFC	2.836418	3.403651	6.240069	-0.56723
PSI	2.150775	4.483254	6.63403	-2.33248

By leveraging the influence of each dimension on the others, we have constructed an influence map to elucidate the intricate interrelationships among these dimensions. This map provides a visual representation of each dimension's contribution to the others. Please refer to Figure 1 for the diagram.

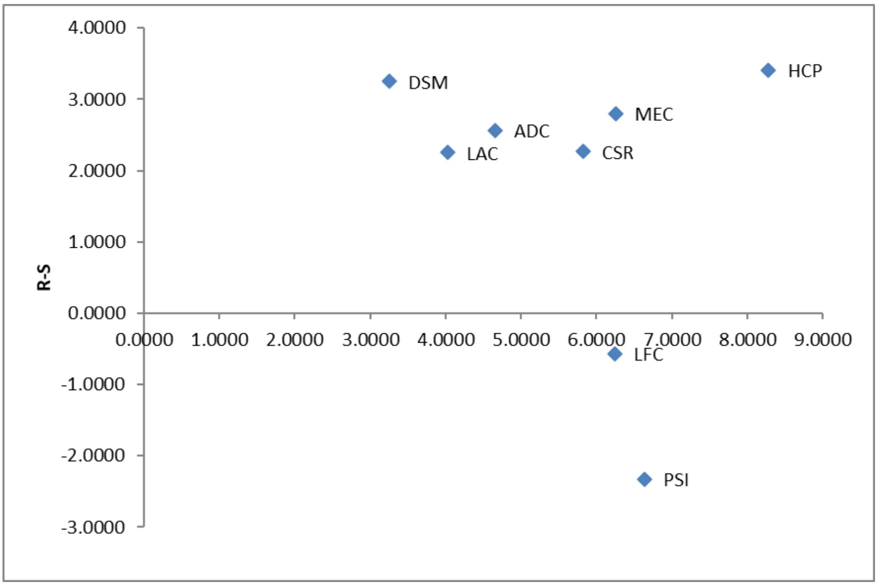

Fig. 1. Relative Causal strengths of factors

Figure 1 reveals that the most influential barriers that inhibit the deployment of green hydrogen are high cost of production, followed by the low durability of storage materials. High Cost of Production (HCP) can result in Limited Availability of Compressors (LAC) as there may be budget constraints for investing in essential equipment. They may also drive the need for Adaptability to different compositions (ADC) to optimize resource utilization and cost-effectiveness. Lack of Flow Control Systems (LFC) can exacerbate Production System Inefficiencies (PSI) by preventing precise control of hydrogen flow rates, potentially leading to inefficiencies and losses. Adaptability to different compositions (ADC) is essential to overcome Production System Inefficiencies (PSI) by efficiently utilizing varying feedstock compositions.

5 Concluding Remarks

In this research article, we have conducted a comprehensive analysis of the roadblocks hindering the deployment of green hydrogen energy through the utilization of the Decision Making Trial and Evaluation Laboratory (DEMATEL) methodology. This approach allowed us to not only identify critical barriers but also to quantify their interrelationships, providing valuable insights into their relative importance within the green hydrogen ecosystem. The findings of this study shed light on several key roadblocks, including high production costs, limited availability of compressors, complex steam reforming processes, and low durability of storage materials. Furthermore, the study highlights the intricate web of causal relationships among these factors, emphasizing their interconnected nature.

Building on the insights gained from this study, future research endeavors can investigate and develop advanced technologies that can mitigate the identified roadblocks. For instance, research into cost-effective and durable materials for hydrogen storage can play a pivotal role in enhancing the feasibility of green hydrogen production. Studies may explore methods for scaling up microbial electrolysis cells (MECs) while maintaining production rates and system efficiencies.

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