Energy Storage and Conversion 2025, 3(4), 3891.
doi: https://doi.org/10.59400/esc3891

Article

Comparative evaluation of green hydrogen production methods using the Pugh matrix technique

Afrin[1], Adeel H. Suhail[1], Fiseha M. Guangul[2], Abdalellah Mohmmed[2,*], Abdul Nazeer[1]

[1] Department of Civil and Mechanical Engineering, Middle East College, Muscat 124, Oman
[2] School of Engineering, Infrastructure and Sustainability, De Montfort University, Dubai P.O. Box 501870, United Arab Emirates
*** Corresponding author:** Abdalellah Mohmmed, abdalellah.mohammed@dmu.ac.uk

CITATION

Afrin, Suhail AH, Guangul FM, et al. Comparative evaluation of green hydrogen production methods using the Pugh matrix technique. Energy Storage and Conversion. 2025; 3(4): 3891.
https://doi.org/10.59400/esc3891

ARTICLE INFO

Received: 29 September 2025
Revised: 3 November 2025
Accepted: 10 November 2025
Available online: 4 December 2025

Abstract: Hydrogen plays a vital role as an energy carrier in the global effort to combat climate change, with significant applications in sectors such as transportation and ammonia production. However, traditional hydrogen production methods are heavily carbon-intensive, with over 98% of hydrogen derived from fossil fuels. This primarily occurs through steam methane reforming (76%) and coal gasification (22%). While steam methane reforming is cost-effective, it generates approximately 9 kg of CO_2 per kg of hydrogen. Consequently, advancing green hydrogen production methods has become a critical area of research. This study explores and compares various green hydrogen production techniques powered by renewable energy sources, including solar, wind, hydro, biomass, and hybrid systems. Production methods such as electrolysis, thermal, chemical, photonic, and biological processes are evaluated using a Pugh matrix, accounting for factors including efficiency, hydrogen yield, resource availability, operating conditions, cost, and greenhouse gas emissions. The findings indicate that alkaline electrolysis currently represents the most viable option for green hydrogen production. These findings affirm alkaline electrolysis as the most appropriate near-term technology for large-scale green hydrogen implementation in Oman and the GCC, while also advocating for the ongoing development of PEM and emerging pathways to ensure long-term diversification. Ultimately, this study provides a clear and practical decision-support framework for the strategic selection of hydrogen technologies in renewable-rich arid regions.

Keywords: green hydrogen; Pugh matrix technique; renewable energy; fossil fuels; water splitting

1. Introduction

Global energy demand is rising due to population growth, industrial expansion, urbanization, and rapid technological advancement [1]. Currently, fossil fuels remain the predominant source of energy for electricity generation, transportation, and industrial processes, resulting in substantial emissions of greenhouse gases (GHGs) and air pollutants, including CO_2, NO_x, SO_x, and particulate matter [2]. The energy sector alone accounts for nearly three-quarters of global greenhouse gas emissions, thereby constituting the primary contributor to climate change [3]. In response, international initiatives have increasingly concentrated on attaining net-zero carbon emissions by 2050, with the aim of restricting the global temperature increase to 1.5 °C, as delineated in major global energy roadmaps [3]. Realizing these ambitious objectives necessitates a fundamental transformation of energy production systems, emphasizing a significant transition toward low-carbon and carbon-free energy carriers.

Hydrogen offers unique advantages as an energy vector, including high gravimetric energy density, versatility in end-use applications, and zero carbon emissions at the point of use [4, 5]. Beyond its conventional role in ammonia and methanol production, hydrogen is increasingly recognized as a strategic medium for long-duration and seasonal energy storage and for sector coupling between electricity, industry, transport, and synthetic fuel production [6, 7]. In power-to-gas-to-power (P2G2P) systems, surplus renewable electricity can be converted into hydrogen via electrolysis, stored for extended periods, and reconverted to electricity or used as an industrial feedstock. Although the round-trip efficiency of such chains typically remains below 35–40%, hydrogen remains one of the few technically viable options for large-scale and seasonal energy storage [8–10]. Moreover, hydrogen–ammonia coupling provides an attractive pathway for long-distance energy transport and export, particularly in regions with established ammonia infrastructure and strong renewable resource potential [11,12].

Recent state-of-the-art studies increasingly emphasize that hydrogen production technologies cannot be evaluated in isolation but must be assessed within integrated energy storage and conversion systems. Large-scale system analyses highlight electrolysis-based hydrogen as a cornerstone of future low-carbon energy systems, enabling long-duration storage, renewable curtailment mitigation, and sector coupling [13–16]. Techno-economic assessments indicate that alkaline and PEM electrolysis currently dominate commercial deployment, while solid oxide electrolysis remains at the demonstration stage due to durability and system-integration challenges. Parallel research underscores the growing importance of hydrogen conversion to ammonia and synthetic fuels to improve volumetric energy density, transportability, and export competitiveness, particularly for renewable-rich regions [17,18].

Hydrogen can be utilized in transportation, power generation, industrial heating, and chemical manufacturing, particularly in ammonia and methanol production [19,20]. When produced using renewable energy sources, hydrogen, commonly referred to as "green hydrogen", offers a pathway to deep decarbonization that is difficult to achieve through direct electrification alone. The current hydrogen production remains overwhelmingly carbon-intensive. More than 98% of global hydrogen production relies on fossil fuel–based methods, primarily steam methane reforming (SMR) and coal gasification, which collectively contribute substantial CO_2 emissions, approximately 9 kg of CO_2 per kg of hydrogen produced via SMR [21]. This reality has intensified global research efforts to identify sustainable, environmentally benign hydrogen production technologies powered by renewable energy sources such as solar, wind, hydropower, and biomass. The literature has extensively examined a diverse array of green hydrogen production technologies, encompassing water electrolysis (including alkaline, proton exchange membrane, and solid oxide methods), thermochemical water splitting, photonic processes, and biomass-based pathways [4, 21–23]. These technologies differ significantly in terms of efficiency, hydrogen yield, operating conditions, cost, resource availability, and technological maturity. While many studies have focused on thermodynamic, techno-economic, or exergy-based evaluations of individual hydrogen production routes [23–25], fewer have addressed the comparative selection problem: how to systematically identify the most suitable green hydrogen production method when multiple, often conflicting, criteria must be considered simultaneously.

Existing comparative studies often utilize sophisticated multi-criteria decision-making (MCDM) tools, such as AHP, TOPSIS, or fuzzy-based methodologies. While these tools are highly effective, they necessitate extensive data, hierarchical structuring, and expert judgment, which may not always be readily accessible, particularly in the context of emerging hydrogen markets [4, 22]. Consequently, there is a practical necessity for transparent and low-complexity decision-making frameworks that can facilitate early-stage planning, policy development, and technology evaluation. Moreover, a significant gap exists in the regional contextualization of green hydrogen technology selection. The majority of published studies adopt a global or generic perspective, with limited consideration of country-specific factors such as renewable resource availability, water constraints, infrastructure readiness, and economic priorities. This limitation is particularly pertinent for countries in the Middle East and North Africa (MENA) region, where renewable energy potential is substantial, yet techno-economic and environmental conditions vary considerably across locations.

Oman represents a strategically essential and underexplored case for green hydrogen deployment. The country has one of the world's highest levels of solar irradiation, ample land, and strong ambitions to diversify its energy mix and reduce dependence on fossil fuels. At the same time, Oman faces challenges related to water scarcity, infrastructure development, and cost competitiveness, making the selection of an appropriate hydrogen production technology a critical decision [26, 27]. Choosing a suboptimal technology could lead to high costs, inefficient resource utilization, or delayed adoption, undermining national decarbonization objectives. Despite these strategic considerations, there is a lack of structured, technology-selection studies specifically tailored to Oman's context. Existing research largely focuses on resource assessments or individual technology analyses, without offering a systematic comparison of green hydrogen production pathways that balances technical performance, economic feasibility, operational conditions, and environmental impact.

To bridge this gap, the present study uses the Pugh matrix decision-making technique to assess 15 green hydrogen production methods against six critical criteria: efficiency, hydrogen yield, raw material availability, required operating conditions, cost, and greenhouse gas emissions. The Pugh matrix is selected for its simplicity, transparency, and appropriateness for early-stage technology evaluation, rendering it particularly advantageous for policymakers, planners, and engineers in nascent hydrogen economies. This study offers a comprehensive comparative analysis of major green hydrogen production technologies through a structured yet accessible decision-making framework. It highlights the trade-offs among competing technologies across multiple performance criteria, thereby facilitating a clearer understanding of their relative strengths and limitations. Additionally, it provides insights specific to Oman to support strategic decision-making for sustainable hydrogen deployment. By addressing both methodological and regional gaps, this work aims to support informed and pragmatic decisions toward the large-scale adoption of green hydrogen in Oman and other regions rich in renewable resources.

2. Materials and methods

This study employs a structured multi-criteria evaluation framework to identify the most suitable green hydrogen production technology, accounting for technical, economic, and environmental considerations. The methodology integrates a comprehensive review of green hydrogen production pathways with a Pugh matrix decision-making technique to rank alternative technologies transparently and systematically. An extensive review of peer-reviewed journal articles, International Energy Agency reports, and recent review studies was conducted to identify relevant green hydrogen production pathways [4, 5, 21, 28]. Based on this review, fifteen hydrogen production methods were selected for evaluation, representing the most prominent renewable-based and low-carbon hydrogen production routes discussed in the literature. The identified technologies were classified into five major categories: electrolysis-based processes, thermolysis and thermochemical water-splitting processes, photonic processes, biological biomass-based processes, and thermochemical biomass-based processes. This classification facilitates a systematic comparison across fundamentally different production mechanisms while ensuring comprehensive coverage of current green hydrogen technologies. The overall classification of green hydrogen production technologies is illustrated in **Figure 1**, adapted from [22,29].

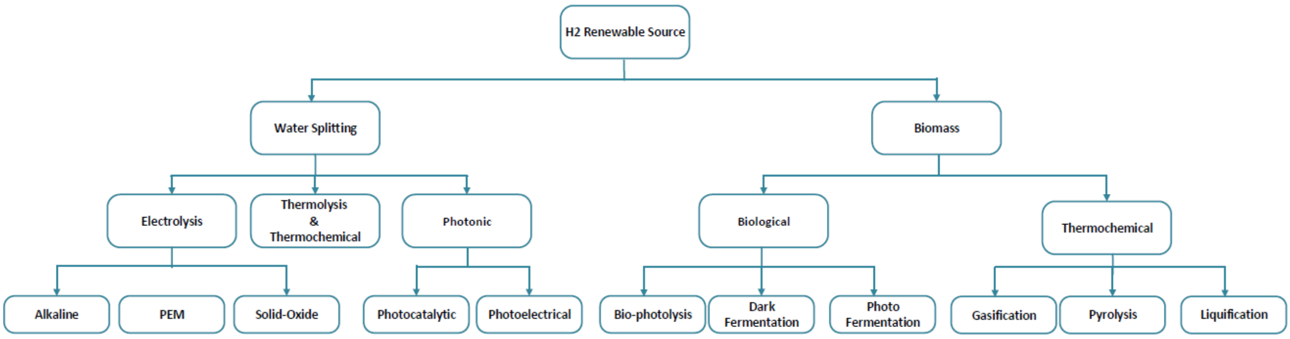


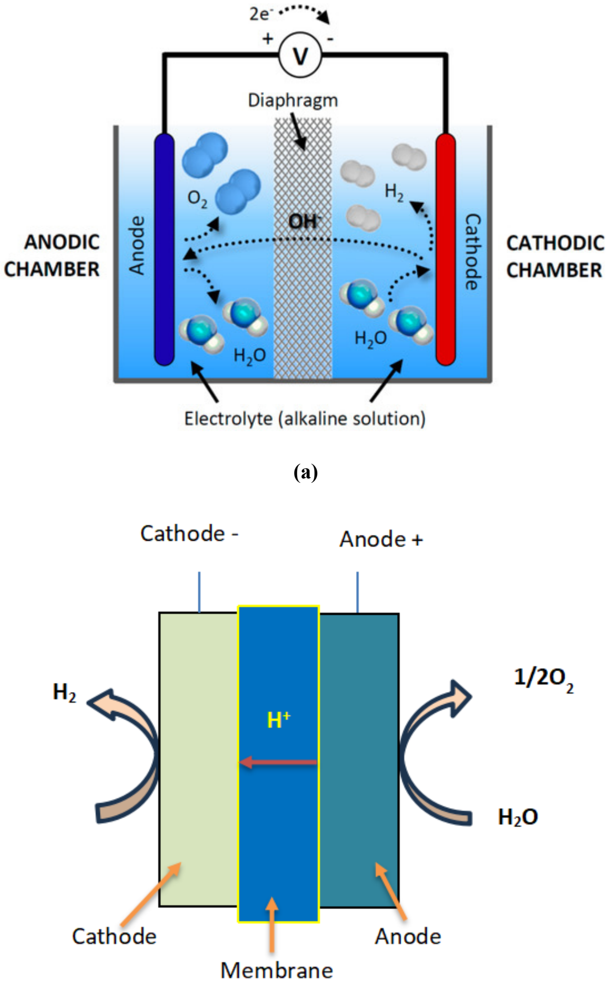
Figure 1. Green hydrogen production technologies.

2.1. Electrolysis

Electrolysis is a process in which water is decomposed into hydrogen and oxygen gases at two electrodes immersed in a liquid medium. The electrochemical cell, comprising solely pure water and two electrodes connected to an external power source, constitutes the core of an electrolysis unit. Upon reaching the critical voltage between the electrodes, hydrogen gas is generated at the cathode, which is negatively charged, while oxygen gas is produced at the anode, which is positively charged.

There are primarily three types of water electrolysis: (a) Alkaline Electrolysis. Alkaline water electrolysis was the first commercially viable water electrolysis technology and remains the most prevalent today. This method utilizes energy to dissociate water molecules into hydrogen and oxygen, with the requisite electrical energy for producing green hydrogen potentially sourced from renewable energy [30]. (b) Proton

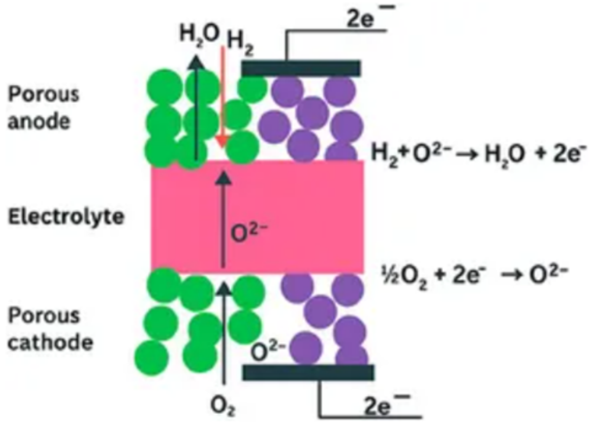
Exchange Membrane (PEM) Electrolysis. The proton exchange membrane (PEM) water electrolysis technique, initially developed by General Electric for fuel cell applications and subsequently for electrolysis, employs a polymeric proton exchange membrane as the solid electrolyte. Nafion is the most widely used membrane, consisting of a sulfonated fluorinated polymer. The thickness of the Nafion membrane ranges from 25 to 250 µm, with the specific thickness required for a given application determined by the operating conditions of the electrolyzer. The efficiency of electrolysis is enhanced with increased membrane thickness. (c) Solid Oxide Electrolysis (SOE). Solid oxide electrolysis (SOE) is increasingly recognized for its enhanced capability to generate ultra-pure hydrogen and convert electrical energy into chemical energy. The operational temperature of a solid oxide electrolyzer, typically ranging from 800 to 1000 °C, sets it apart from both alkaline and proton exchange membrane (PEM) systems. At these elevated temperatures, steam is introduced into the electrolyzer instead of water. The primary components of SOE include two porous electrodes and a dense ionic conducting electrolyte. Yttria-stabilized zirconia (YSZ) is the most frequently utilized electrolyte in SOE, owing to its robust mechanical strength and high oxygen-ion conductivity [31,32]. The schematic diagrams for alkaline electrolysis, PEM electrolysis, and Solid oxide electrolysis are shown in **Figure 2**.



(a)

(b)

Figure 2. *Cont.*



(c)

Figure 2. **(a)** Alkaline electrolyser [33]; **(b)** PEM electrolysis; **(c)** Solid oxide electrolysis [34].

2.2. Thermolysis and thermochemical water splitting

Thermolysis and thermochemical water splitting are methodologies that employ thermal energy to produce hydrogen from water. Thermolysis is a single-step process that involves the dissociation of water and necessitates a high-temperature energy source exceeding 2500 K. It is crucial to achieve adequate dissociation to prevent the formation of an explosive mixture. This requirement imposes stringent demands on the materials due to the extremely high temperatures involved. Thermochemical water splitting, in contrast, entails a sequence of cyclic chemical reactions that ultimately result in the dissociation of water into hydrogen and oxygen. Notably, this process frequently does not necessitate the use of a catalyst or a membrane for the separation of hydrogen and oxygen. The operational temperature generally ranges from 600 to 1200 K. Employing higher temperatures reduces the number of cycles required for thermochemical water splitting. Moreover, the incorporation of electrical energy to facilitate the process introduces the concept of hybrid cycles [35]. Various chemicals and metals can be employed in distinct thermochemical water splitting cycles. Notably, the two-step and three-step thermochemical cycles represent the fundamental forms [36, 37]. **Figure 3** shows the thermolysis reaction of thermochemical water-splitting processes.

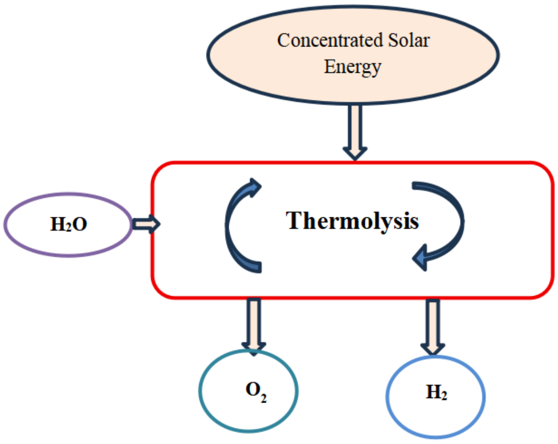


Figure 3. Thermolysis reaction.

In the two-step thermochemical cycles depicted in **Figure 4**, a metal oxide in a low valence state can undergo reduction to form the metal and release oxygen. Alternatively, a metal oxide with a higher valence state may be reduced to produce a metal oxide with a lower valence state. In this process, a temperature range of 1700–3000 K must be supplied by the heat source, and a solar collector can be utilized to harness concentrated solar radiation. To date, the primary limitations of this type of thermochemical cycle include the necessity of materials that can withstand very high temperatures and the relatively lower efficiency of two-step thermochemical cycles compared to electrolysis [37].

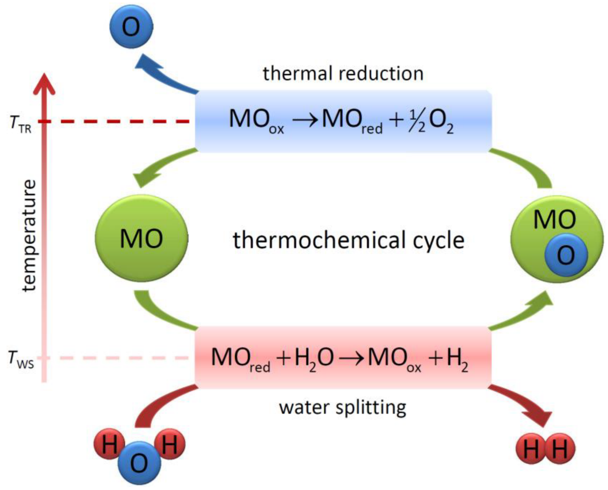


Figure 4. Two-step thermochemical metal oxide cycle [38].

Three-step processes can be derived from two-step processes by replacing the reaction that occurs at the highest temperature with a two-step reaction process. This alteration serves to lower the maximum temperature requirement for the cycle. The Sulphur-Iodine (S-I) cycle, also referred to as the General Electric cycle, is the most prominent example within this category. It was initially proposed in the 1970s by General Electric [37]. A schematic diagram of the Hybrid Sulfur cycle is presented in **Figure 5**.

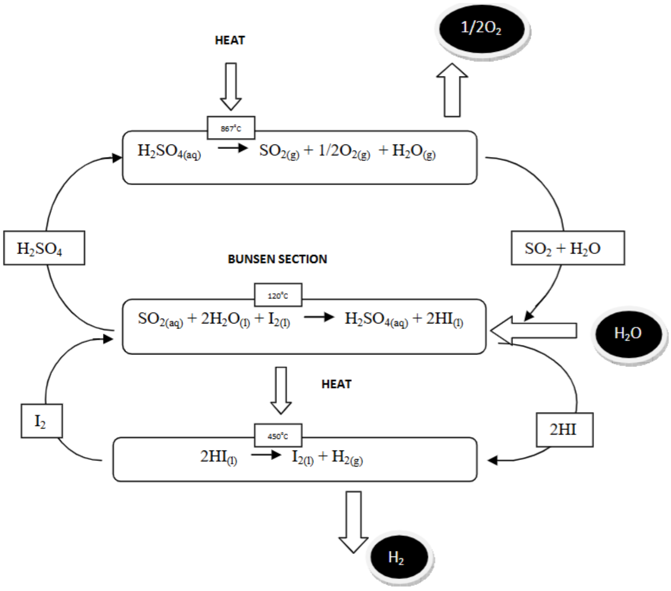


Figure 5. Schematic diagram for a three-step S-I thermochemical cycle [39].

2.3. Photonic process

Hydrogen can also be produced using a photonic process in which photon energy is used. This can be classified into two processes: photocatalytic and photoelectrochemical (also known as photoelectrolysis) water splitting.

2.3.1. Photocatalytic water splitting

The photocatalytic process uses direct sunlight in the presence of a photocatalyst, such as titanium oxide (TiO_2), which is used in powdered form and dispersed in water. Light will be radiated in this water, and the water will split into hydrogen and oxygen. This is a very flexible and cheap method of hydrogen production. The benefit of photocatalysts is that water splitting can occur in the homogeneous phase without the need for transparent electrodes or direct illumination. However, there are some disadvantages and challenges of employing this method in large-scale production.

In a photocatalytic cell, a semiconductor such as platinum (Pt) or Titanium oxide (TiO_2) can be considered a photoelectrochemical cell, which provides both oxidation and reduction at its surface. It happens in a series of steps. **Figure 6** shows the schematic representation of photocatalytic overall water splitting on a metal-loaded semiconductor (such as Pt/TiO_2) particle system [40].

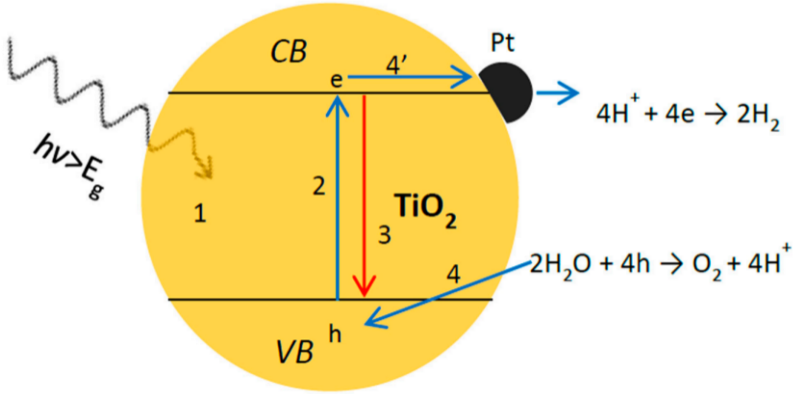


Figure 6. Process of the photocatalytic system [40].

2.3.2. Photoelectrochemical

The basic principle behind photoelectrochemical water decomposition, shown in **Figure 7**, is that light energy is converted into electricity in a cell made up of two electrodes submerged in an aqueous electrolyte, one of which must be made of a semiconductor to absorb light. Water is then electrolyzed using this power. Numerous photoelectrode materials, including WO_3, Fe_2O_3, and TiO_2, have been researched for usage as thin films in the photoelectrochemical process, and TiO_2 is found to be the most promising photoelectrode for this reaction [41].

2.4. Biomass process

Biomass can undergo two distinct processes: biological and thermochemical processes. The primary biological processes encompass bio-photolysis and fermentation, with bio-photolysis further categorized into direct and indirect bio-photolysis. Similarly, fermentation can be classified as dark fermentation and photo-fermentation.

Thermochemical conversion stands out as the leading technology for producing hydrogen from biomass, building on methodologies used in biofuels such as biomethane, which is derived from steam methane reforming (SMR). The three main thermochemical routes involved in this process are gasification, pyrolysis, and aqueous phase reforming [21].

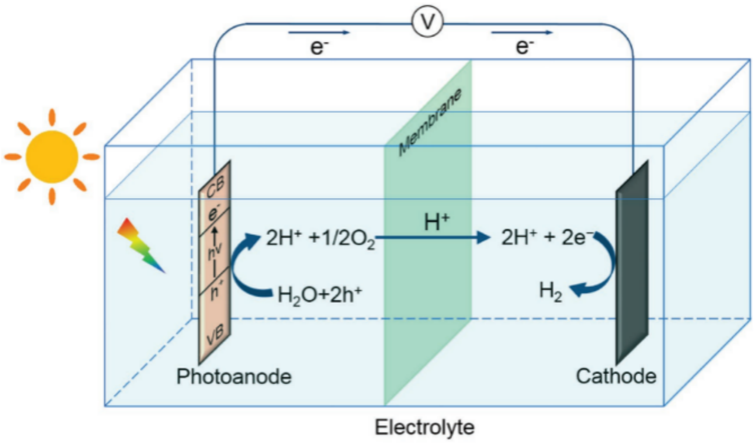


Figure 7. Process of photoelectrochemical cell (PEC) water splitting [42].

2.4.1. Biological process

Biophotolysis

There are two types of biophotolytic H_2 generation processes: Direct and indirect biophotolysis. Direct biophotolysis is a straightforward water-splitting mechanism that produces biohydrogen in either cyanobacteria or green algae. Various types of microalgae are used for biophotolysis, but the most used species is the microalgae Chlamydomonas reinhardtii (C. reinhardtii). Green algae in anoxic conditions can convert around 22% of the light energy by using hydrogen as an electron donor during carbon dioxide fixation, even at low light intensities. Green microalgae produce hydrogen in the dark under anaerobic conditions to support hydrogen metabolism.

Indirect biophotolysis was created to solve the issue of oxygen suppression of biohydrogen synthesis in direct biophotolysis. Cyanobacteria (green-blue algae) and Chlamydomonas reinhardtii are the most commonly used in this process. Production of biohydrogen and the separation of oxygen are the two steps in this process. Photosynthesis in an open pond converts atmospheric CO_2 into carbohydrates and oxygen, serving as the primary phase of the oxygen separation process, which comprises two stages. The subsequent stage involves inducing anaerobic, dark conditions in a closed bioreactor, where the generated carbohydrates are metabolized to yield acetic acid and biohydrogen [43].

Fermentation

Biomass rich in carbohydrates can be used as a renewable resource to assist photoheterotrophic (light fermentation) and anaerobic (dark fermentation) microorganisms in their production of biohydrogen. Dark fermentation is one of the most promising biological pathways for producing biohydrogen. It occurs under anaerobic conditions in the absence of light and uses the fermentative conversion of organic substrates and biomass to biohydrogen. Organic waste can also be used in this process to form hydrogen. The pH, organic food, feed rate of nutrients, temperature, solids retention time, and partial pressure of hydrogen must all be controlled in the dark fermentation process in order to enhance the hydrogen yield [43].

In photofermentation or light fermentation, light energy is converted into biomass, and photosynthetic bacteria break down a variety of substrates to produce hydrogen. In this procedure, organic acids such as acetate, lactate, and butyrate are converted by purple nonsulfur (PNS) photosynthetic bacteria, such as Rhodobacter species, under anaerobic and anoxic conditions. Bacteria absorb solar energy, produce Adenosine triphosphate (ATP) through their photosynthetic mechanism, and use nitrogenase to turn organic acids into Hydrogen. The nitrogenase enzyme is responsible for producing hydrogen in this method as well. Because purple non-Sulphur bacteria can perform anoxygenic photosynthesis, in which no oxygen is evolved, there are no issues during photo fermentation despite nitrogenase being oxygen-sensitive. As a result, the nitrogenase activity is not inhibited, which is a significant advantage over the direct biophotolysis [22,44].

2.4.2. Thermochemical process for biomass

One of the most efficient ways to extract hydrogen-rich gases from biomass is using thermochemical processes. The key tenets used in these technologies include gasification, pyrolysis, and hydrothermal liquefaction.

Gasification is the thermochemical breakdown of biomass at high temperatures (800–900 °C) in a limited-oxygen environment. Various product ratios, including H_2, CO, CO_2, CH_4, C_xH_x, and tars, are generated depending on operating parameters, such as temperature, catalysts, and the gasification medium. A catalyst used during gasification will accelerate the cracking reaction and lower the activation energy, thereby reducing energy consumption. Various types of catalysts are used, but the nickel-based catalyst showed better performance [45–50].

Pyrolysis resembles gasification but occurs at lower temperatures (400–800 °C) and is carried out without oxidizing agents. Therefore, the pyrolysis of biomass yields three distinct products: a liquid called bio-oil, a solid called bio-char, and a gaseous product called syngas. The relative proportions of these products are influenced by factors such as the composition of the feedstock and the pyrolysis process parameters. Pyrolysis can be categorized into two main types: rapid (fast) pyrolysis and traditional pyrolysis, depending on the specific operational conditions. Fast pyrolysis, which involves high temperatures and short residence times, is chosen for hydrogen production because charcoal is the main byproduct of conventional pyrolysis. Catalytic pyrolysis utilizes metal-based catalysts, such as Ni or alkali metals, or non-metal-based catalysts, such as activated carbon. Both have demonstrated their capability to enhance the production of hydrogen [48–50].

Hydrothermal liquefaction is a relatively low-temperature (300–400 °C), high-pressure (40–200 bar) process that produces bio-oil from a relatively wet biomass in the presence of a catalyst and hydrogen. A liquid biocrude, along with hydrogen and other byproducts, is the major outcome of this process [51].

2.5. Green hydrogen production method selection

Selecting an optimal green hydrogen production pathway in Oman and the broader Gulf Cooperation Council (GCC) region is a complex multi-criteria decision-making (MCDM) challenge. While the region boasts some of the highest levels of solar irradiation globally, abundant land resources, and a strong governmental commitment to hydrogen export and energy diversification, it also confronts significant constraints. These include acute water scarcity, harsh operational conditions, infrastructure readiness issues, and the need to compete on cost with fossil-fuel-based hydrogen [52–54]. The unique characteristics of specific regions highlight the need for a decision-support framework that effectively balances technical performance, resource availability, operational feasibility, economic viability, and environmental impact. Relying solely on single-criterion or purely economic optimization approaches is inadequate. Consequently, structured Multi-Criteria Decision-Making (MCDM) techniques have gained prominence in the assessment of hydrogen technology, particularly in arid and resource-constrained regions such as Oman and the Gulf Cooperation Council (GCC) [55–57].

In this study, we employ the Pugh matrix decision-making technique to evaluate and prioritize green hydrogen production technologies suitable for implementation in Oman and comparable GCC environments. The Pugh matrix functions as a comparative evaluation tool, facilitating the assessment of multiple alternatives against a common set of criteria relative to a defined baseline [57]. While advanced multi-criteria decision-making (MCDM) methods such as AHP, TOPSIS, PROMETHEE, and ELECTRE have been widely applied in studies of hydrogen and renewable energy [58–60], the Pugh matrix is particularly well-suited for the early-stage strategic technology selection required in the Omani and GCC hydrogen roadmap for several reasons: Compatibility with early-phase hydrogen planning: Oman's green hydrogen sector is currently in a scaling and infrastructure-development phase. At this stage, decision-makers necessitate a transparent and adaptable screening tool rather than a data-intensive optimization model. The Pugh matrix facilitates rapid comparison of multiple production routes under conditions of limited or evolving data [57, 61]. Equal-level evaluation of interdependent criteria: In the GCC context, criteria such as efficiency, water use, operating conditions, and cost are strongly interrelated. Hierarchical decomposition, as required by AHP, may oversimplify these interactions. The Pugh matrix permits all criteria to be evaluated at the same level, which aligns more closely with the integrated nature of hydrogen system challenges in arid regions [62]. Transparency for policy and industrial stakeholders: Hydrogen development in Oman involves multiple stakeholders, including policymakers, utilities, investors, and export-oriented industries. The intuitive scoring structure of the Pugh matrix enhances interpretability and facilitates stakeholder engagement and consensus-building [63]. Proven relevance in engineering and process selection: The Pugh matrix has been extensively applied in engineering design, process selection, and sustainability-driven technology screening, rendering it well-suited for the comparative assessment of hydrogen production technologies under region-specific constraints [57,64].

2.6. Criteria definition and weighting with regional relevance

The Pugh matrix is implemented through a structured seven-step procedure that explicitly considers Oman/GCC conditions.

Step 1: Definition of Alternatives—The alternatives consist of technically viable hydrogen production pathways that can be integrated with Oman's renewable energy potential, particularly solar and wind resources, and aligned with export-oriented hydrogen strategies.

Step 2: Definition of Evaluation Criteria—Six criteria have been identified following a comprehensive review of hydrogen production technologies and the principal regional challenges impacting the deployment of green hydrogen in Oman and the GCC. These criteria are as follows: Energy efficiency, which underscores the necessity to optimize output from renewable electricity resources; Hydrogen yield, which affects land use, scalability, and export potential; Raw material availability, with a particular focus on access to water and feedstocks in arid environments; Required operating conditions, which consider high ambient temperatures, dust, and infrastructure constraints; Cost, which continues to be a significant barrier to the competitiveness of green hydrogen in the region; and Emissions, which are aligned with Oman's decarbonization and net-zero objectives. These criteria collectively address the technical, environmental, and socio-economic realities of hydrogen production in arid, high-temperature regions [53,55,56,65].

Step 3: Criteria Prioritization—The criteria are ranked in descending order of importance based on their relevance to overcoming the dominant barriers to green hydrogen competitiveness in Oman. Efficiency and hydrogen yield are prioritized due to the capital-intensive nature of renewable-based hydrogen systems, followed by raw material availability and operating conditions, which are critical in water-scarce and high-temperature environments. Cost and emissions, while still essential, are ranked lower due to ongoing policy support and long-term decarbonization commitments.

Step 4: Assignment of Relative Weightages—Linear weightages from 6 (highest priority) to 1 (lowest priority) are assigned to the criteria. This weighting scheme reflects strategic priorities specific to Oman's hydrogen ambitions while maintaining simplicity and methodological transparency [61].

Step 5: Baseline Selection—A conventional hydrogen production pathway or a reference green hydrogen method is selected as the baseline and assigned a neutral score of zero, enabling relative comparison across alternatives.

Step 6: Evaluation Scale Definition—A discrete qualitative-to-quantitative evaluation scale is adopted (**Table 1**), ranging from *Excellent* (+3) to *Not acceptable* (−2). This scale allows expert judgment to be systematically translated into numerical values while accommodating uncertainty typical of emerging hydrogen technologies.

Step 7: Score Aggregation and Ranking—Weighted scores are calculated by multiplying criterion weightages with the corresponding evaluation scale values. The aggregated scores are then used to rank hydrogen production pathways according to their suitability for deployment in Oman and the GCC.

Table 1. Evaluation scale points.

Description	Scale
Excellent	+3
Very good	+2
Good	+1
Acceptable/OK	0
Poor	−1
Not acceptable	−2

2.7. Sensitivity analysis in the regional context

A sensitivity analysis is conducted to assess the robustness of the technology rankings under uncertainty in criterion importance. Criterion weightages are varied by ±10–20% to reflect alternative policy priorities, such as increased emphasis on water availability or cost reduction. This analysis is particularly relevant in the Oman/GCC context, where hydrogen strategies are evolving in response to infrastructure development, desalination integration, and export market dynamics [63,66]. The results confirm whether the preferred production pathway remains dominant across plausible regional scenarios.

3. Results and discussion

The Pugh matrix methodology was applied to evaluate fifteen green hydrogen production pathways using six criteria relevant to the Oman/GCC context: efficiency, hydrogen yield, raw material availability, required operating conditions, cost, and greenhouse gas (GHG) emissions. The results provide a structured comparison of the relative suitability of each technology for deployment under arid-climate and resource-constrained conditions.

3.1. Criterion-level performance analysis

From an efficiency perspective, proton exchange membrane (PEM) electrolysis, solid oxide electrolysis (SOEC), and hydrogen liquefaction achieved the highest weighted scores. These technologies benefit from advanced electrochemical and thermodynamic characteristics that allow high conversion efficiencies [53, 55]. However, high efficiency alone does not guarantee regional suitability, particularly in Oman, where water scarcity, operational robustness, and capital cost remain dominant constraints [67]. In terms of hydrogen yield, alkaline electrolysis emerged as the leading technology. This outcome reflects its proven capability for continuous large-scale hydrogen production and its compatibility with industrial-scale deployment, both of which are essential for export-oriented hydrogen strategies envisioned in Oman and the GCC [68, 69]. Raw material availability is a critical factor in arid regions. Alkaline electrolysis, fermentation-based routes, gasification, pyrolysis, and liquefaction achieved the highest scores in this category due to their reliance on widely available materials or mature supply chains. In contrast, PEM electrolysis and photoelectrochemical routes scored lower because of their reliance on scarce noble metals and specialized membranes, which increase supply-chain vulnerability and costs [70,71].

Regarding operating conditions, alkaline electrolysis and PEM electrolysis performed strongly due to their moderate temperature and pressure requirements. These characteristics enhance reliability and safety under Oman's high ambient temperatures and dust-prone environments, compared to high-temperature thermochemical cycles that require complex thermal management systems [72]. Cost analysis indicated that photolysis, fermentation, gasification, pyrolysis, and liquefaction achieved relatively favourable scores. However, many of these technologies remain at laboratory or pilot scales and face significant challenges related to efficiency, scalability, and system integration, limiting their short-term applicability in the GCC [73, 74]. For GHG emissions, electrolysis-based routes powered by renewable electricity achieved the highest scores, confirming their potential for near-zero operational emissions. In contrast, biomass and thermochemical conversion pathways exhibited comparatively higher emissions due to upstream processing and auxiliary energy requirements [53,75].

Although the present analysis adopts a structured qualitative–quantitative MCDM approach, the ranking outcomes are broadly consistent with reported quantitative performance indicators in the literature. Typical specific electricity consumption for alkaline and PEM electrolysis ranges between 48–55 kWh kg^{-1} H_2, corresponding to system efficiencies of 65–75%, while solid oxide electrolysis may exceed 80% under high-temperature operation but with significantly higher system complexity. When embedded in power-to-gas-to-power chains, overall round-trip efficiencies decline to approximately 35–40%, highlighting the importance of coupling hydrogen primarily to long-duration storage, industrial feedstocks, and ammonia or synthetic fuel production rather than short-term grid balancing [76, 77]. Incorporating such thermodynamic and techno-economic performance indicators into future extensions of the present framework would further strengthen the robustness of technology selection for large-scale deployment in Oman.

3.2. Overall ranking and technology prioritization

The aggregated weighted scores (**Table 2**) reveal that alkaline electrolysis achieved the highest overall score: 55, followed by PEM electrolysis: 50, and solid oxide electrolysis: 39. A significant performance gap exists between these leading technologies and the remaining alternatives, indicating a clear preference for electrolysis-based hydrogen production in the Oman/GCC context. This result highlights the importance of balanced performance across multiple criteria rather than optimization of a single parameter. Technologies that scored highly in efficiency but poorly in cost or material availability were outperformed by mature electrolysis systems that offer robustness and scalability.

Table 2. Production processes and the results of the Pugh matrix.

Criteria	Weight	Baseline	Electrolysis				Thermochemical water split			Photonic		Biological processes			Thermochemical processes		
			Alkaline	PEM	Solid oxide	Ther-molysis	Two steps (Mox)	Three steps (S-I)	Photo-catalytic water split	PEC	Direct photo-lysis	Indirect photo-lysis	Dark ferment-ation	Photo ferment-ation	Gasifi-cation	Pyrolysis	Liquification
Efficiency	6	0	6 × 2 = 12	6 × 3 = 18	6 × 3 = 18	6 × (−1) = −6	6 × 0 = 0	6 × 1 = 6	6 × (−2) = −12	6 × (−2) = −12	6 × 2 = 12	6 × (−2) = −12	6 × 1 = 6	6 × (−2) = −12	6 × 1 = 6	6 × 0 = 0	6 × 3 = 18

Table 2. *Cont.*

Criteria	Weight	Baseline	Electrolysis				Thermochemical water split			Photonic			Biological processes		Thermochemical processes		
			Alkaline	**PEM**	**Solid oxide**	**Ther-molysis**	**Two steps (Mox)**	**Three steps (S-I)**	**Photo-catalytic water split**	**PEC**	**Direct photo-lysis**	**Indirect photo-lysis**	**Dark ferment-ation**	**Photo ferment-ation**	**Gasifi-cation**	**Pyrolysis**	**Liquification**
Yield	5	0	5 × 3 = 15	5 × 2 = 10	5 × 1 = 5	5 ×(−1) = −5	5 × 0 = 0	5 × 1 = 5	5 × (−2) = −10	5 ×(−1) = −5	5 × (−2) = −10	5 × (−2) = −10	5 × 1 = 5	5 × 1 = 5	5 × 1 = 5	5 × (−1) = −5	5 × (−2) = −10
Raw Material Availability	4	0	4 × 3 = 12	4 × 2 = 8	4 × 2 = 8	4 × 1 = 4	4 × 1 = 4	4 × 1 = 4	4 × 2 = 8	4 × 2 = 8	4 × 1 = 4	4 × 1 = 4	4 × 3 = 12	4 × 3 = 12	4 × 3 = 12	4 × 3 = 12	4 × 3 = 12
Required Condition	3	0	3 × 3 = 9	3 × 3 = 9	3 × 1 = 3	3 × (−1) = −3	3 × 0 = 0	3 × 1 = 3	3 × 1 = 3	3 × 1 = 3	3 × 3 = 9	3 × 3 = 9	3 × 3 = 9	3 × 3 = 9	3 × 0 = 0	3 × 1 = 3	3 × 1 = 3
Cost	2	0	2 × 2 = 4	2 × 1 = 2	2 × 1 = 2	2 × (−1) = −2	2 × 1 = 2	2 × 1 = 2	2 × (−2) = −4	2 × (−2) = −4	2 × 3 = 6	2 × 3 = 6	2 × 3 = 6	2 × 3 = 6	2 × 3 = 6	2 × 3 = 6	2 × 3 = 6
Emission	1	0	1 × 3 = 3	1 × 3 = 3	1 × 3 = 3	1 × 3 = 3	1 × 3 = 3	1 × 3 = 3	1 × 3 = 3	1 × 3 = 3	1 × 3 = 3	1 × 3 = 3	1 × (−1) = −1	1 × (−1) = −1	1 × (−1) = −1	1 × (−1) = −1	1 × (−1) = −1
Total			**55**	**50**	**39**	**−9**	**9**	**23**	**−12**	**−7**	**24**	**0**	**37**	**19**	**28**	**15**	**28**

The evaluation scale used in the Pugh matrix is as follows:

Evaluation Scale	**Value**
Excellent	3
Very Good	2
Good	1
Acceptable	0
Poor	−1
Very Poor	−2

3.3. Comparative discussion: Alkaline vs. PEM electrolysis

Alkaline electrolysis ranked first due to its technological maturity, cost-effectiveness, and operational simplicity. Operating at moderate temperatures (50–80 °C) and pressures (up to 30 bar), it is well suited for large-scale deployment in Oman. The use of low-cost electrolytes such as potassium hydroxide (KOH) or sodium hydroxide (NaOH), along with non-noble metal catalysts, significantly enhances economic viability and material availability [68, 78].

PEM electrolysis ranked second, benefiting from higher efficiency (up to 90%), compact system design, and high hydrogen purity (up to 99.9%). These features make PEM particularly attractive for integration with variable renewable energy sources such as solar and wind [79]. However, its reliance on platinum-group metals and polymer membranes increases capital cost and supply-chain risk, which currently limits its competitiveness for large-scale deployment in Oman [70, 80]. While PEM technology is expected to improve as material costs decline and recycling pathways mature, alkaline electrolysis remains the most practical near-term solution for Oman due to its established industrial base and lower economic risk.

3.4. Implications for Oman and the GCC

The findings suggest that alkaline electrolysis currently represents the most appropriate technology for green hydrogen production in Oman, considering regional limitations related to water availability, cost sensitivity, climatic conditions, and infrastructure readiness. Proton exchange membrane (PEM) electrolysis serves as a robust complementary option, particularly for prospective decentralized or flexible operational scenarios. Other production methods, such as thermochemical cycles, photolysis, and biological processes, hold promise for long-term diversification but necessitate significant technological advancement before they can be adopted on a large scale in the Gulf Cooperation Council (GCC) region.

4. Conclusion

Hydrogen is anticipated to assume a pivotal role in future low-carbon energy systems, particularly in the decarbonization of sectors that are challenging to abate and in facilitating the export of renewable energy. Nevertheless, the sustainability and competitiveness of hydrogen are critically contingent upon the selection of suitable production technologies. This study assessed fifteen green hydrogen production methods utilizing a structured Pugh matrix decision-making framework specifically adapted to the Oman/GCC context. Six efficiency criteria which are: hydrogen yield, raw material availability, required operating conditions, cost, and greenhouse gas emissions, were employed to encapsulate the technical, economic, and environmental dimensions pertinent to arid regions.

The findings suggest that alkaline electrolysis and PEM electrolysis are the most viable methods for green hydrogen production, with total scores of 55 and 50, respectively. Alkaline electrolysis outperforms PEM in terms of yield, material availability, cost, and technological maturity, whereas PEM exhibits superior efficiency and hydrogen purity. Given Oman's existing infrastructure, climate, and cost constraints, alkaline electrolysis is identified as the most suitable short-term solution for large-scale green hydrogen implementation. Therefore, it is recommended that alkaline electrolysis be prioritized for near- and medium-term hydrogen initiatives in Oman and the GCC. Meanwhile, PEM electrolysis should be supported through targeted research, development, and pilot projects, particularly for integration with variable renewable energy sources. Additionally, emerging technologies such as photolysis, thermochemical cycles, and biological routes should continue to be explored as part of a long-term hydrogen diversification strategy.

While the Pugh matrix offers a transparent and practical framework for decision support, it is important to acknowledge several limitations. The method's reliance on expert judgment may introduce subjectivity, influenced by regional experience and data availability. Additionally, the linear weighting approach does not explicitly account for nonlinear trade-offs between water consumption, energy efficiency, and cost, which are critical considerations in arid regions such as Oman. Furthermore, the Pugh matrix generates relative rankings rather than absolute performance metrics. Despite these limitations, when combined with sensitivity analysis and region-specific criteria definition, the method provides a robust and defensible approach for early-stage screening of green hydrogen technology in Oman and the GCC. Future research should incorporate quantitative techno-economic analysis and water–energy nexus modeling to complement the qualitative MCDM approach. The proposed methodology offers a transparent and robust framework for the early-stage selection of hydrogen technologies and can be readily adapted to other arid, resource-constrained regions pursuing green hydrogen development.

Author contributions: Each author played a significant role at various stages of the research process, culminating in the final report as detailed below. A: Responsible

for conceptualizing the research topic, developing the methodology, conducting data collection and analysis, and drafting the research report. AHS: Provided guidance and supervision throughout the research, ensured the validation of results and analyses, and contributed to the editing of the report. FMG: Oversaw the research methodology, conducted a thorough revision of the research report, prepared the manuscript for publication, and validated the data and findings. AM: Focused on validating the analysis and results, editing and refining the manuscript, and formatting it according to journal submission standards. AN: Assisted with data collection and analysis, while also contributing to the editing of the research report. All authors have read and agreed to the published version of the manuscript.

Funding: This work received no external funding.

Institutional review board statement: Not applicable.

Informed consent statement: Not applicable.

Data availability statement: Not applicable.

Acknowledgment: The authors express their gratitude to the Civil and Mechanical Engineering Programme at Middle East College for facilitating and providing all the essential support throughout the completion of this project work.

Conflict of interest: The authors declare no conflict of interest.

References

1. Guangul FM, Chala GT. SWOT analysis of wind energy as a promising conventional fuels substitute. In: Proceedings of the 2019 4th MEC International Conference on Big Data and Smart City (ICBDSC); 2019; Muscat, Oman. pp. 1–6.
2. Citaristi I. International energy agency—IEA. In: The Europa Directory of International Organizations 2022. Routledge; 2022. pp. 701–702.
3. International Energy Agency (IEA). Net Zero by 2050: A Roadmap for the Global Energy Sector. International Energy Agency; 2021.
4. Dincer I. Green methods for hydrogen production. International Journal of Hydrogen Energy. 2012; 37(2): 1954–1971.
5. Dincer I, Joshi AS. Solar Based Hydrogen Production Systems. Springer; 2013. Volume 553.
6. Khaleel M, Bashir S, Al-Ansari T, et al. Towards hydrogen sector investments for achieving sustainable electricity generation. Journal of Solar Energy and Sustainable Development. 2024; 13(1): 71–96.
7. Al-Breiki M, Bicer Y. Sustainable Energy Carriers for Energy Storage and Transport: Exploring Advanced Solutions for a Green Future. Springer Nature; 2025.
8. Landler A. Capacity Expansion Modeling of Hydrogen and Electricity with Sector Coupling in New England [PhD Thesis]. Massachusetts Institute of Technology; 2023.
9. Ratz H, West K, Liebman J, et al. The Role of Long-Duration Energy Storage in Deep Decarbonization: Policy Considerations. World Resources Institute; 2025.
10. Beck HP, Kuehne M, Sauer DU, et al. A comprehensive review of sustainable energy systems in the context of the German energy transition—part 2: Renewable energy and storage technologies. Carbon Neutral Systems. 2025; 1(1): 13.
11. Salmon N, Bañares-Alcántara R. Green ammonia as a spatial energy vector: A review. Sustainable Energy & Fuels. 2021; 5(11): 2814–2839.
12. Negro V, Noussan M, Chiaramonti D. The potential role of ammonia for hydrogen storage and transport: A critical review of challenges and opportunities. Energies. 2023; 16(17): 6192.

13. Ivanov P, Zhuk A. Thermodynamic modeling of the Power-to-Gas technology with methane and hydrogen as a chemical storage. Energy Storage and Conversion. 2025; 3(3).
14. Guangul FM, Chala GT. A comparative study between the seven types of fuel cells. Applied Science and Engineering Progress. 2020; 13(3): 185–194.
15. Wang X, Zhang Y, Liu Z, et al. Roadmap toward the production, storage, transportation, and applications of green hydrogen. Carbon and Hydrogen. 2025; 27(3): 241–267.
16. Kishk A. State-of-the-Art and Technologies in Hydrogen Production and Distribution. 2023. Available online: https://aaltodoc.aalto.fi/server/api/core/bitstreams/0aa2da49-8296-4872-9572-d4f46f30e521/content (accessed on 7 August 2025).
17. Algburi S, Faeq A, Ahmed A, et al. The green hydrogen role in the global energy transformations. Renewable and Sustainable Energy Transition. 2025; 8: 100118.
18. Kurre SK, Singh R, Kumar A, et al. Sustainable Hydrogen Technology and Global Energy Transition. Ashok Yakkaldevi; 2025.
19. Bockris JO. The origin of ideas on a hydrogen economy and its solution to the decay of the environment. International Journal of Hydrogen Energy. 2002; 27(7–8): 731–740.
20. Marbán G, Valdés-Solís T. Towards the hydrogen economy? International Journal of Hydrogen Energy. 2007; 32(12): 1625–1637.
21. Lepage T, Itouchène M, Courson C, et al. Biomass-to-hydrogen: A review of main routes production, processes evaluation and techno-economical assessment. Biomass and Bioenergy. 2021; 144: 105920.
22. Agyekum EB, Nutakor C, Agwa AM, et al. A critical review of renewable hydrogen production methods: Factors affecting their scale-up and its role in future energy generation. Membranes. 2022; 12(2): 173.
23. Yilanci A, Dincer I, Ozturk HK. A review on solar-hydrogen/fuel cell hybrid energy systems for stationary applications. Progress in Energy and Combustion Science. 2009; 35(3): 231–244.
24. Ni M, Leung MK, Leung DY. Energy and exergy analysis of hydrogen production by a proton exchange membrane (PEM) electrolyzer plant. Energy Conversion and Management. 2008; 49(10): 2748–2756.
25. Safari F. Development and Analysis of Alternative Thermochemical Cycles for Hydrogen Production [PhD Thesis]. Ontario Tech University; 2021.
26. Barghash H, Al-Suleimani A, Al-Habsi S, et al. Achieving decarbonization considering green hydrogen production: Case study of Oman. Results in Engineering. 2024; 23: 102657.
27. Sial NR, Al-Abri M, Al-Hinai A, et al. Techno-economic assessment of green hydrogen production in unexploited landlocked northern-western region of Oman to realize national sustainable strategy. International Journal of Hydrogen Energy. 2024. 137: 892–904.
28. Younus HA, Al Hajri R, Ahmad N, et al. Green hydrogen production and deployment: opportunities and challenges. Discover Electrochemistry. 2025; 2(1): 32.
29. Dincer I, Acar C. Review and evaluation of hydrogen production methods for better sustainability. International Journal of Hydrogen Energy. 2015; 40(34): 11094–11111.
30. Chisholm G, Zhao T, Cronin L. Hydrogen from water electrolysis. In: Storing Energy. Elsevier; 2022. pp. 559–591.
31. Elder R, Cumming D, Mogensen MB. High temperature electrolysis. In: Carbon Dioxide Utilisation. Elsevier; 2015. pp. 183–209.
32. Ni M, Leung MK, Leung DY. Technological development of hydrogen production by solid oxide electrolyzer cell (SOEC). International Journal of Hydrogen Energy. 2008; 33(9): 2337–2354.
33. Rodríguez J, Amores E. CFD modeling and experimental validation of an alkaline water electrolysis cell for hydrogen production. Processes. 2020; 8(12): 1634.
34. Raman R, Kumar S, Gupta A, et al. Energy-efficient parameter estimation of solid oxide fuel cells under varying pressure conditions using the Black Widow optimization algorithm. Frontiers in Energy Research. 2025; 13: 1659232.
35. Sundén B. Hydrogen, Batteries and Fuel Cells. Academic Press; 2019.
36. Rozzi E, Minuto FD, Lanzini A, et al. Green synthetic fuels: Renewable routes for the conversion of non-fossil feedstocks into gaseous fuels and their end uses. Energies. 2020; 13(2): 420.
37. Safari F, Dincer I. A review and comparative evaluation of thermochemical water splitting cycles for hydrogen production. Energy Conversion and Management. 2020; 205: 112182.
38. Roeb M, Neises M, Monnerie N, et al. Materials-related aspects of thermochemical water and carbon dioxide splitting: a review. Materials. 2012; 5(11): 2015–2054.

39. Nyoni B. Simulation of the Sulphur Iodine Thermochemical Cycle [PhD Thesis]. North-West University; 2011.
40. Nadeem MA, Khan MA, Idrees F, et al. An overview of the photocatalytic water splitting over suspended particles. Catalysts. 2021; 11(1): 60.
41. El-Shafie M, Kambara S, Hayakawa Y. Hydrogen production technologies overview. Journal of Power and Energy Engineering. 2019. 7: 107–154.
42. Xu XT, Pan L, Zhang X, et al. Rational design and construction of cocatalysts for semiconductor-based photo-electrochemical oxygen evolution: a comprehensive review. Advanced Science. 2019; 6(2): 1801505. doi: 10.1002/advs.201801505
43. Azwar M, Hussain M, Abdul-Wahab A. Development of biohydrogen production by photobiological, fermentation and electrochemical processes: A review. Renewable and Sustainable Energy Reviews. 2014; 31: 158–173.
44. Chandrasekhar K, Lee YJ, Lee DW. Biohydrogen production: Strategies to improve process efficiency through microbial routes. International Journal of Molecular Sciences. 2015; 16(4): 8266–8293.
45. Guangul F, Sulaiman S, Ramli A. Gasification of Oil Palm Fronds with Preheated Inlet Air. Universiti Teknologi PETRONAS; 2013.
46. Guangul FM, Sulaiman SA, Raghavan VR. Gasification and effect of gasifying temperature on syngas quality and tar generation: A short review. AIP Conference Proceedings. 2012; 1440: 491–498. doi: 10.1063/1.4704254
47. Guangul F, Sulaiman S, Ramli A. Temperature profile and producer gas composition of high temperature air gasification of oil palm fronds. IOP Conference Series: Earth and Environmental Science. 2013; 16, 012067.
48. Megía PJ, Vizcaíno AJ, Calles JA, et al. Hydrogen production technologies: From fossil fuels toward renewable sources. A mini review. Energy & Fuels. 2021; 35(20): 16403–16415.
49. Guangul FM, Sulaiman SA, Ramli A. Study of the effects of operating factors on the resulting producer gas of oil palm fronds gasification with a single throat downdraft gasifier. Renewable Energy. 2014; 72: 271–283.
50. Guangul FM, Sulaiman SA, Ramli A. Gasifier selection, design and gasification of oil palm fronds with preheated and unheated gasifying air. Bioresource Technology. 2012; 126: 224–232.
51. Chen WT, Zhang Y, Zhang J, et al. Renewable diesel blendstocks produced by hydrothermal liquefaction of wet biowaste. Nature Sustainability. 2018; 1(11): 702–710.
52. Pohekar SD, Ramachandran M. Application of multi-criteria decision making to sustainable energy planning—A review. Renewable and Sustainable Energy Reviews. 2004; 8(4): 365–381.
53. Staffell I, Scamman D, Velazquez Abad A, et al. The role of hydrogen and fuel cells in the global energy system. Energy & Environmental Science. 2019; 12(2): 463–491.
54. Wang JJ, Jing YY, Zhang CF, et al. Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renewable and Sustainable Energy Reviews. 2009; 13(9): 2263–2278.
55. Ball M, Weeda M. The hydrogen economy–vision or reality? International Journal of Hydrogen Energy. 2015; 40(25): 7903–7919.
56. Maroufmashat A, Fowler M. Transition of future energy system infrastructure; through power-to-gas pathways. Energies. 2017; 10(8): 1089.
57. Pugh S. Total Design: Integrated Methods for Successful Product Engineering. Addison-Wesley; 1991.
58. Brans JP, Vincke P. Note—A Preference Ranking Organisation Method: (The PROMETHEE Method for Multiple Criteria Decision-Making). Management Science. 1985; 31(6): 647–656.
59. Huynh VN, Yanako Y, Nakamori Y, et al. Multiple-attribute decision making under uncertainty: The evidential reasoning approach revisited. IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans. 2006; 36(4): 804–822.
60. Saaty TL. Decision making with the analytic hierarchy process. International Journal of Services Sciences. 2008; 1(1): 83–98.
61. Otto KN. Product Design: Techniques in Reverse Engineering and New Product Development. Tsinghua University Press; 2003.
62. Dodgson JS, Spackman M, Pearman A, et al. Multi-criteria Analysis: A Manual. Department for Communities and Local Government; 2009.
63. Ishizaka A, Nemery P. Multi-criteria Decision Analysis: Methods and Software. John Wiley & Sons; 2013.
64. Fargier H, Thierry C. The use of possibilistic decision theory in manufacturing planning and control: Recent results in Fuzzy Master Production Scheduling. In: Title of the Book. Springer-Verlag; 2000. pp. 45–59.
65. Benbouzid M, Machmoum M, Feldhoff AF, et al. Global Journey of Green Hydrogen: Opportunities and Challenges. In: Green Hydrogen. Wiley; 2025. pp. 337–371.

66. Isa AHM, Mohd RM. A Hybrid AHP-TOPIS-Based Marine Economic Activities Evaluation Model for Marine Geospatial Data Infrastructure. UNILAG Journal of Transport and Logistics. 2024; 1(1): 55–72.
67. International Energy Agency. Global Hydrogen Review 2023. OECD Publishing; 2023.
68. Buttler A, Spliethoff H. Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. Renewable and Sustainable Energy Reviews. 2018; 82: 2440–2454.
69. Kumar SS, Himabindu V. Hydrogen production by PEM water electrolysis–A review. Materials Science for Energy Technologies. 2019; 2(3): 442–454.
70. Glenk G, Reichelstein S. Economics of converting renewable power to hydrogen. Nature Energy. 2019; 4(3): 216–222.
71. Züttel A, Remhof A, Borgschulte A, et al. Hydrogen: the future energy carrier. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2010; 368(1923): 3329–3342.
72. Laguna-Bercero MA. Recent advances in high temperature electrolysis using solid oxide fuel cells: A review. Journal of Power Sources. 2012; 203: 4–16.
73. Turner J, Sreivatsava G, Oglesby W, et al. Renewable hydrogen production. International Journal of Energy Research. 2008; 32(5): 379–407.
74. Abanades S, Flamant G. Thermochemical hydrogen production from a two-step solar-driven water-splitting cycle based on cerium oxides. Solar Energy. 2006; 80(12): 1611–1623.
75. Acar C, Dincer I. Comparative assessment of hydrogen production methods from renewable and non-renewable sources. International Journal of Hydrogen Energy. 2014; 39(1): 1–12.
76. Xhani E. Performance Analysis of a Hydrogen Production Plant: Efficiency Evaluation of a NaOH Alkaline Electrolyzer [Master's Thesis]. Università Politecnica delle Marche; 2023.
77. Begum S. Techno-Economic Analysis of Hydrogen Production & Storage Technologies for Grid Scale Applications [Master's Thesis]. University of Vaasa; 2024.
78. Zeng K, Zhang D. Recent progress in alkaline water electrolysis for hydrogen production and applications. Progress in Energy and Combustion Science. 2010; 36(3): 307–326.
79. Carmo M, Fritz DL, Mergel J, et al. A comprehensive review on PEM water electrolysis. International Journal of Hydrogen Energy. 2013; 38(12): 4901–4934.
80. Ursua A, Gandia LM, Sanchis P. Hydrogen production from water electrolysis: Current status and future trends. Proceedings of the IEEE. 2011; 100(2): 410–426.