

Green Hydrogen Production Using Air-Conditioner Condensate Wastewater: A Review of Solar-Powered Electrolysis Systems

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Abstract

As the world moves toward sustainable and clean energy solutions, growing attention has been directed toward alternative energy carriers such as Hydrogen (H₂). Hydrogen is considered an attractive energy option due to its high-density energy and ecofriendly properties. However, most conventional H₂ production methods rely on fossil-fuel-based processes such as steam methane reforming and coal gasification, which contribute significantly to greenhouse gas emissions and environmental degradation. As a result, the development of sustainable hydrogen production technologies has become an important focus of contemporary energy research. Water electrolysis supplied by renewable sources like solar and wind energy is increasingly recognised as one of the most promising techniques for green hydrogen generation among the available production pathways. Renewable-energy-driven electrolysis enables hydrogen production without direct carbon emissions and supports the transition toward a low-carbon energy economy. Nevertheless, large-scale electrolysis systems require substantial quantities of purified water, which raises concerns regarding freshwater availability and long-term resource sustainability. Recent studies have therefore explored alternative water resources for hydrogen production, including wastewater streams. In this context, air-conditioner condensate water has gained attention as a relatively clean and underutilised water resource with low total dissolved solids (TDS) and high purity. This review paper examines hydrogen production technologies with particular emphasis on renewable-energy-driven electrolysis and the potential use of air-conditioner (AC) condensate water as an alternative feedwater for sustainable green hydrogen generation.

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INTRODUCTION

In recent decades, the worldwide need for energy has grown substantially owing to industrial expansion, population increase, and continuous technological progress. At present, a large portion of global energy production relies on fossil fuels, such as coal, oil, and natural gas. The extensive use of these energy resources has resulted in serious environmental problems, including greenhouse gas emissions, climate change, and air pollution [1, 2, 3]. Consequently, the development of sustainable and environmentally friendly energy technologies has become a major challenge for modern society.

The use of hydrogen as a fuel results in the formation of water as a byproduct, highlighting its suitability as an environmentally benign energy source. Owing to these advantages, hydrogen is considered an important component of future sustainable energy systems and is widely used in applications such as fuel cells, power generation, and transportation [4, 5, 6].

Although these technologies are well-established and economically viable, they produce significant carbon dioxide emissions and contribute to global warming. Therefore, researchers have increasingly focused on developing sustainable hydrogen production technologies that reduce environmental impacts.

Nevertheless, large-scale hydrogen production via electrolysis requires a considerable amount of purified water. Conventional electrolysis systems generally require deionized or highly purified water to ensure efficient electrochemical reactions and to prevent electrode degradation. Considering the growing scarcity of freshwater resources in many regions, the use of alternative water sources for hydrogen production has become an important area of research.

In response to this issue, attention has been directed toward alternative water resources, such as seawater, municipal wastewater, and industrial effluents, for hydrogen generation. Wastewater-based hydrogen production technologies offer the advantage of simultaneously treating wastewater and generating renewable energy, thereby improving overall resource efficiency and environmental sustainability [7, 8, 9].

Among the various alternative water sources, air-conditioner condensate water has recently gained attention as a relatively clean and underutilized resource. As part of the cooling process, air-conditioning units remove humidity from indoor air and generate condensate water as a secondary output of the process. This water generally contains low levels of TDS and is relatively pure compared with many other wastewater sources. Consequently, it shows promise for use as a feedwater supply in electrolysis-driven hydrogen generation systems.

This review paper aims to provide a comprehensive overview of hydrogen production technologies, with particular emphasis on renewable-energy-driven electrolysis systems and the utilization of alternative water resources. Special attention has been given to the physicochemical characteristics of air-conditioner condensate water and its potential application for sustainable green hydrogen production [10, 11, 12].

Several studies have investigated different hydrogen production technologies using renewable energy and alternative water resources. Table 1 summarizes the major research contributions related to green hydrogen production technologies, renewable energy integration, and wastewater-based hydrogen generation.

Hydrogen Production Technologies

Hydrogen can be produced through several technological pathways, depending on the feedstock, energy source, and production process. These technologies are generally classified into thermochemical, electrochemical, biological and photochemical methods. The selection of a hydrogen production method depends on several factors, including energy efficiency, environmental impact, economic feasibility, and technological maturity [13, 14, 15].

SMR is economically attractive and widely implemented; however, it generates significant carbon dioxide emissions and contributes to climate change.

Coal gasification is another commonly adopted technique for hydrogen production, particularly in regions with rich coal reserves. During this process, coal reacts with steam and oxygen under high-temperature conditions to form synthesis gas containing mainly hydrogen, carbon monoxide, and carbon dioxide. Although it can yield large volumes of hydrogen, the process contributes considerably to greenhouse gas emissions and environmental degradation.

Table 1. Summary of literature review on green hydrogen production.

S.N.	Author(s)	Year	Paper title	Research focus	Key findings
1	[16]	2023	Hydrogen Production Methods Based on Solar and Wind Energy: A Review.	Renewable hydrogen production	Solar and wind powered electrolysis can significantly reduce carbon emissions
2	[17]	2025	Sustainable Green Hydrogen Production Through Integrating Electrolysis, Water Treatment and Solar Energy.	Integrated renewable hydrogen systems	Combining solar energy and electrolysis improves sustainability
3	[18]	2025	Investigation and Analysis of Solar and Wind Energy Potential for Green Hydrogen Production via Alkaline Water Electrolysis.	Renewable electrolysis systems	Hybrid renewable systems increase hydrogen production efficiency
4	[19]	2025	Environmental Assessment of Hydrogen Production from Wastewater Using Solar PV PEM Electrolysis.	Solar powered electrolysis	Renewable electrolysis significantly reduces environmental impacts
5	[20]	2025	Hydrogen Production Through Electrolysis of Industrial Wastewater: Prospects and Challenges.	Wastewater hydrogen production	Industrial wastewater can serve as alternative feedwater
6	[21]	2023	Acidification-Based Direct Electrolysis of Treated Wastewater for Hydrogen Production and Water Reuse.	Wastewater electrolysis	Direct electrolysis of treated wastewater improves water reuse
7	[22]	2025	Hydrogen Production from Winery Wastewater Through a Dual-Chamber Microbial Electrolysis Cell.	Bio-hydrogen production	Microbial electrolysis enables simultaneous wastewater treatment
8	[23]	2026	Solar-Powered Electrochemical Processes for Sustainable Wastewater Treatment and Green Hydrogen Production.	Solar electrochemical systems	Electrochemical systems can produce hydrogen during wastewater treatment
9	[24]	2013	A Comprehensive Review on PEM Water Electrolysis.	Electrolysis technology	PEM electrolysis offers high efficiency and compact design
10	[15]	2010	Recent Progress in Alkaline Water Electrolysis for Hydrogen Production.	Alkaline electrolysis	Alkaline electrolysis is a mature hydrogen production technology
11	[12, 13, 14]	2012	Hydrogen Production from Water Electrolysis: Current Status and Future Trends.	Electrolysis systems	Electrolysis technologies are essential for green hydrogen production
12	[10, 11]	2004	Sustainable Hydrogen Production	Solar hydrogen	Renewable hydrogen is important for future sustainable energy systems
13	[25]	2010	Solar Water Splitting Cells	Photoelectrochemical hydrogen production	Solar water splitting enables direct renewable hydrogen production
14	[26, 27, 28]	2008	Microbial Electrolysis Cells for Hydrogen Production	Bioelectrochemical hydrogen	Organic waste streams can be converted to hydrogen
15	[29]	2008	Hydrogen Production Using Bioelectrochemical Systems	Wastewater bioelectrochemical systems	Bioelectrochemical systems improve energy recovery

16	[30]	2019	Hydrogen Production by PEM Water Electrolysis – A Review	Electrolysis technologies	PEM electrolysis provides high hydrogen purity
17	[31]	2017	Recovery and Reuse of HVAC Condensate Water for Sustainable Water Management	Condensate water reuse	AC condensate water has low TDS and high reuse potential
18	[32]	2018	Characterization and Reuse Potential of Air-Conditioner Condensate Water	HVAC condensate water	Condensate water can be reused for sustainable water management
19	[33]	2021	Urban Building Condensate Water Recovery and Reuse Potential	Urban water recovery	Buildings generate significant condensate water resources
20	[34]	2019	Water Reuse Potential of Air Conditioner Condensate	Water treatment	Low TDS water sources are suitable for electrochemical applications

In recent years, there has been a growing emphasis on sustainable hydrogen production methods that use renewable energy sources.

When the electrolysis system is supplied with electricity generated from renewable sources, such as solar or wind energy, the H_2 produced is known as green hydrogen. This process eliminates direct carbon emissions and supports the transition to low-carbon energy systems.

Currently, hydrogen production mainly relies on three electrolysis technologies: alkaline water electrolysis (AWE), proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis (SOE). Alkaline electrolysis is one of the oldest and most commercially mature techniques, in which an alkaline electrolyte, such as potassium hydroxide, is used to support ion movement between the electrodes. Solid oxide electrolysis operates at high temperatures and can achieve higher efficiencies because part of the required energy is supplied as heat [35, 36].

In addition to electrochemical processes, biological hydrogen production technologies, such as microbial electrolysis cells and dark fermentation, have been investigated. These systems use microorganisms to convert organic matter in wastewater or biomass into hydrogen through bioelectrochemical reactions. Such approaches provide the additional benefit of simultaneous wastewater treatment and energy recovery [37, 38].

Overall, hydrogen production technologies continue to evolve as global efforts toward decarbonization increase. Among the various methods available, renewable energy-driven electrolysis is widely considered the most sustainable pathway for large-scale green hydrogen production because of its compatibility with renewable electricity and minimal environmental impact.

Hydrogen can be produced through several thermochemical, electrochemical, and biological processes, depending on the feedstock and energy source used. Each hydrogen production technology differs in terms of efficiency, operational conditions, environmental impact, and technological maturity. Table 2 provides a comparative overview of the major hydrogen production methods and their respective characteristics.

Renewable Energy Based Hydrogen Production

The growing concerns over climate change and environmental degradation have accelerated the development of renewable energy technologies for sustainable hydrogen production. Renewable energy sources such as solar, wind, hydro, and geothermal energy offer environmentally friendly alternatives to fossil fuels and play an important role in the production of green hydrogen. When renewable electricity is used to power electrolysis systems, hydrogen can be produced without direct carbon emissions, making it a key component of future low-carbon energy systems.

Table 2. Comparison of hydrogen production technologies.

S.N.	Hydrogen production method	Feedstock / energy source	Operating conditions	Typical efficiency (%)	Advantages	Limitations	Ref.
1	Steam Methane Reforming (SMR)	Natural gas + steam	700–1000 °C catalytic reactor	65–75	Mature technology, large scale hydrogen production	High CO ₂ emissions, fossil fuel dependency	[16]; [39]
2	Coal Gasification	Coal + oxygen + steam	High temperature gasification	55–65	Suitable for coal-rich regions	High greenhouse gas emissions	[39]; [10,11]
3	Partial Oxidation	Hydrocarbon fuels	High temperature oxidation	60–70	Fast hydrogen production	Produces CO ₂ emissions	[39]
4	Autothermal Reforming	Natural gas + oxygen + steam	Combined reforming process	60–75	Higher efficiency compared to SMR	Still fossil fuel dependent	[16]
5	Alkaline Water Electrolysis (AWE)	Electricity + water	60–80 °C with alkaline electrolyte (KOH)	60–70	Commercially mature, relatively low cost	Slow dynamic response	[15]; [30]
6	Proton Exchange Membrane (PEM) Electrolysis	Renewable electricity + water	50–80 °C polymer membrane	65–80	High efficiency, compact design	Expensive noble metal catalysts	[24]; [30]
7	Solid Oxide Electrolysis (SOEC)	Electricity + high temperature heat	700–1000 °C ceramic electrolyte	80–90	Very high efficiency due to thermal energy	Material degradation issues	[12, 13, 14]
8	Photoelectrochemical Water Splitting	Solar radiation	Semiconductor photoelectrodes	5–15	Direct solar-to-hydrogen conversion	Low efficiency and stability	[25]
9	Photocatalytic Water Splitting	Solar energy + catalyst	Ambient temperature	1–10	Simple system design	Low hydrogen production rate	[25]
10	Solar Thermochemical Water Splitting	Concentrated solar thermal energy	>800 °C thermochemical cycles	30–50	High theoretical efficiency	Complex reactor systems	[16]
11	Dark Fermentation	Biomass / organic waste	Anaerobic microbial process	20–40	Utilizes organic waste	Low hydrogen yield	[26, 27, 28]
12	Photo-Fermentation	Organic acids + light energy	Biological fermentation	20–35	Renewable biological hydrogen	Low conversion efficiency	[26, 27, 28]
13	Microbial Electrolysis Cell (MEC)	Wastewater + electricity	Bioelectrochemical reactor	30–50	Simultaneous wastewater treatment and hydrogen production	System complexity	[26, 27, 28]; [29]

14	Biomass Gasification	Biomass feedstock	High temperature gasification	35–50	Renewable biomass resource	Tar formation and purification challenges	[10, 11]
15	Methane Pyrolysis	Methane	High temperature thermal decomposition	60–70	Produces hydrogen without CO ₂ emissions	High energy requirement	[40]
16	Electrochemical Wastewater Reforming	Wastewater + electricity	Electrochemical reactors	30–60	Wastewater treatment with hydrogen recovery	Variable wastewater composition	[20]

Among the various renewable energy sources, solar energy has received significant attention because of its widespread availability and rapidly decreasing installation costs. Solar photovoltaic (PV) systems convert sunlight directly into electricity, which can be used to power water electrolysis systems for hydrogen production. Solar-driven hydrogen production systems are particularly suitable for regions with high solar irradiance and favorable climatic conditions. In such systems, photovoltaic panels generate electricity that drives the electrolysis process, splitting water molecules into hydrogen and oxygen.

Wind energy is another promising renewable energy source for hydrogen production. Wind turbines convert kinetic energy from the wind into electrical energy, which can then be used to power electrolysis units. Wind-based hydrogen production systems are particularly effective in coastal regions and open landscapes where wind resources are abundant. Studies have shown that wind-powered electrolysis systems can achieve reliable hydrogen production under favorable wind conditions.

Despite these advantages, renewable energy sources such as solar and wind energy are inherently intermittent. Variations in solar radiation and wind speed can cause fluctuations in the power supply, which may affect the stable operation of electrolysis systems. To overcome this limitation, researchers have proposed hybrid renewable energy systems that combine multiple renewable sources, such as solar and wind energy, with energy storage technologies. These hybrid systems can provide a more stable electricity supply and improve the overall efficiency of hydrogen production.

In addition, renewable energy-driven electrochemical systems have been investigated for both hydrogen production and wastewater treatment. In such integrated systems, renewable electricity can drive electrochemical reactions that simultaneously remove pollutants from wastewater while producing hydrogen gas at the cathodes. These systems contribute to sustainable water and energy management and support the concept of circular resource economies.

Overall, renewable energy-based hydrogen production is one of the most promising pathways for achieving sustainable energy systems. The integration of renewable electricity generation technologies with advanced electrolysis systems can significantly reduce greenhouse gas emissions and enhance energy security. Continued technological advancements are expected to improve system efficiency, reduce operational costs, and enable the large-scale deployment of green hydrogen production technologies in the future.

Wastewater as an Alternative Water Source for Hydrogen Production

The increasing demand for hydrogen production through water electrolysis has raised concerns regarding the large consumption of freshwater resources for this purpose. Conventional electrolysis systems typically require highly purified or deionized water to ensure efficient electrochemical reactions and to prevent electrode degradation. However, freshwater availability is already limited in

many regions owing to population growth, industrial expansion, and climate change. Consequently, the exploration of alternative water resources for hydrogen production has become an important area of research.

Wastewater has emerged as a promising alternative resource for hydrogen production because of its widespread availability and resource recovery potential. Municipal and industrial wastewater streams often contain dissolved ions, organic compounds, and nutrients that can participate in electrochemical reactions. In recent years, researchers have investigated various electrochemical and bioelectrochemical technologies that utilize wastewater as a feedstock for hydrogen production.

One of the major advantages of wastewater-based hydrogen production systems is the possibility of achieving dual benefits. These systems can simultaneously generate hydrogen energy while treating wastewater and removing pollutants. Electrochemical wastewater treatment technologies, such as electrocoagulation, electro-oxidation, and microbial electrolysis cells, have been widely studied for their ability to convert organic waste into hydrogen while improving water quality.

Industrial wastewater is another significant resource for hydrogen production research. Many industrial processes generate wastewater streams containing high concentrations of organic and chemical substances. Through appropriate electrochemical or biological processes, these waste streams can be converted into valuable energy resources, thereby reducing environmental pollution.

In addition to industrial wastewater, treated municipal wastewater has been explored as a potential feedwater source for hydrogen production through electrolysis. After undergoing treatment processes to remove suspended solids and contaminants, treated wastewater may possess suitable physicochemical properties for electrolysis with minimal purification. Recent studies have demonstrated that the direct electrolysis of treated wastewater can achieve promising hydrogen production efficiencies under controlled conditions.

Another important area of research involves the use of seawater for hydrogen production. Seawater is an abundant water resource; however, its direct use in electrolysis systems poses several challenges. High salt concentrations, chloride ions, and other impurities can lead to electrode corrosion and undesirable side reactions. Consequently, researchers are currently developing advanced catalysts and membrane technologies to improve the feasibility of seawater electrolysis systems.

Overall, the use of alternative water resources, such as wastewater and seawater, for hydrogen production offers a promising solution to address both water scarcity and sustainable energy generation. By integrating wastewater treatment with hydrogen production technologies, systems that simultaneously address environmental challenges and energy demands can be created. These developments have opened up new research opportunities for sustainable hydrogen production using unconventional water resources.

Air Conditioner Condensate Water Characteristics and Potential for Hydrogen Production

Air-conditioning systems are widely used in residential, commercial, and industrial buildings to maintain indoor thermal comfort. During the cooling process, warm humid air passes over the evaporator coil of the air-conditioning unit, causing the moisture present in the air to condense. This condensed moisture is collected as air-conditioner condensate water, which is typically discharged as waste water. However, this water represents a relatively clean and underutilized resource that can potentially be reused for various applications, including irrigation, cooling systems, and electrochemical processes such as hydrogen production.

Various water sources have been investigated for hydrogen production through electrolysis. Each water source possesses different physicochemical characteristics that influence the electrolysis

efficiency and system performance. Table 3 presents a comparison of different water resources used for hydrogen production, highlighting the potential advantages of using air conditioner condensate water as an alternative feedwater source.

Air-conditioner condensate water is generally characterized by low total dissolved solids (TDS), low mineral content, and near-neutral pH values. As water is formed through the condensation of atmospheric moisture, its chemical composition is often similar to that of distilled water. Previous studies have reported that the TDS concentration of condensate water typically ranges between 10 and 50 ppm, which is significantly lower than that of municipal water supplies and most wastewater streams. This relatively high purity makes condensate water a promising feedwater source for electrolysis-based hydrogen production with minimal pretreatment.

In addition to its favorable chemical characteristics, air-conditioning condensate water is generated in significant quantities in buildings where air-conditioning systems operate continuously. The amount of condensate water produced depends on the environmental humidity, temperature, cooling capacity, and operating duration of the air-conditioning system. Studies have indicated that a typical one-ton air-conditioning unit can generate approximately 1–2 liters of condensate water per hour under humid climatic conditions. In large buildings such as hospitals, shopping malls, hotels, and office complexes, the total volume of condensate water produced can reach several hundred liters per day.

The recovery and utilization of condensate water from air-conditioning systems can contribute to sustainable water management in urban areas. Instead of being discharged into the drainage systems, this water can be collected and reused for various purposes. Using air-conditioner condensate water as a feedwater source for hydrogen production systems can reduce freshwater consumption while supporting renewable energy.

Table 3. Comparison of water sources for hydrogen production.

S.N.	Water source	Typical characteristics	Advantages	Limitations	Ref.
1	Deionized Water	Very low TDS (<5 ppm), high purity	High electrolysis efficiency, minimal electrode fouling	Requires expensive purification process	[24]; [30]
2	Municipal Tap Water	Moderate TDS (100–500 ppm)	Easily available water resource	Scaling and mineral deposition may affect electrodes	[16]
3	Seawater	Very high salinity (~35,000 ppm), high chloride content	Abundant water resource globally	Chloride corrosion and side reactions during electrolysis	[7, 8, 9]
4	Industrial Wastewater	Contains organic compounds, chemicals and heavy metals	Simultaneous wastewater treatment and hydrogen production possible	Requires pretreatment and monitoring	[20]
5	Treated Municipal Wastewater	Reduced contaminants after treatment	Reuse of treated water resources	Additional filtration required for electrolysis	[21]
6	Agricultural Wastewater	Organic nutrients and suspended solids	Potential energy recovery from organic matter	High variability in composition	[26, 27, 28]
7	Air Conditioner Condensate Water	Low TDS (10–50 ppm), near-neutral pH	High purity water source with minimal pretreatment requirement	Limited research on electrolysis applications	[31], [32]
8	Rainwater	Low mineral content, naturally collected	Renewable water source suitable for electrolysis	Seasonal availability and storage challenges	[33]

Table 4. Potential of air conditioner condensate water for hydrogen production.

S.N.	Parameter	Typical range / characteristics	Significance for electrolysis	Ref.
1	Water Source	Condensed atmospheric moisture from air conditioning systems	Naturally generated water during cooling process in HVAC systems	[31]
2	Total Dissolved Solids (TDS)	10–50 ppm	Low mineral content reduces electrode scaling and improves electrolysis efficiency	[34]
3	pH Value	6.0–7.5	Near neutral pH suitable for electrochemical reactions	[32]
4	Electrical Conductivity	Low conductivity	May require electrolyte addition for efficient electrolysis	[31]
5	Contaminants	Very low impurities compared to industrial wastewater	Minimal pretreatment required before electrolysis	[33]
6	Water Production Rate	1–2 L per hour per AC unit (humid climate)	Large buildings can generate significant volumes of condensate water	[32]
7	Availability	Residential, commercial and industrial buildings	Potential decentralized water resource for hydrogen production	[33]
8	Environmental Benefit	Utilization of waste condensate water	Reduces freshwater consumption and improves water sustainability	[16]
9	Integration Potential	Compatible with solar powered electrolysis systems	Enables sustainable decentralized hydrogen production	[17]
10	Research Status	Limited studies available	Represents a research opportunity for sustainable hydrogen production	[20]

Another advantage of condensate water is its relatively low impurity content, which reduces the risk of electrode fouling and scaling during the electrolysis process. In conventional electrolysis systems, high concentrations of dissolved salts and impurities can reduce the electrolysis efficiency and damage the electrode materials. Since condensate water contains minimal dissolved solids, it may improve the electrolysis performance and extend the operational lifetime of electrolyzer components.

Furthermore, the integration of renewable energy technologies, such as solar photovoltaic systems, with electrolysis units utilizing condensate water can create decentralized hydrogen production systems suitable for urban environments. In such systems, solar energy provides the electrical power required for electrolysis, and condensate water serves as the feedwater source. This integrated approach supports sustainable energy-water management and contributes to the development of environmentally friendly hydrogen production systems.

Despite its potential advantages, several practical considerations must be addressed before large-scale implementation. These include the development of efficient condensate water collection systems, storage infrastructure, and basic filtration processes to remove dust particles or microbial contaminants. Monitoring variations in water quality owing to environmental conditions is also necessary to ensure stable electrolysis performance. Table 4 illustrates the potential of air conditioner condensate water for hydrogen production.

Overall, condensate water from air conditioners is a promising alternative water resource for electrolysis-based hydrogen production. Its relatively high purity, widespread availability in urban environments, and compatibility with renewable energy systems make it an attractive option for sustainable green hydrogen generation. Further research is required to evaluate the long-term electrolysis performance and techno-economic feasibility of utilizing condensate water for hydrogen production.

Challenges and Limitations in Renewable Hydrogen Production

Despite significant advancements in green hydrogen production technologies, several technical, economic, and operational challenges continue to limit the large-scale implementation of renewable

hydrogen systems. Addressing these challenges is essential for achieving reliable and economically viable hydrogen production using renewable energy sources and alternative water resources such as seawater.

One of the major challenges associated with renewable hydrogen production is the intermittent nature of renewable energy sources, such as solar and wind energy. Solar power generation depends on sunlight availability, which varies with weather conditions, seasonal changes, and day–night cycles. Similarly, wind energy generation is influenced by fluctuating wind speed. These variations can lead to an unstable electricity supply for electrolysis systems, which may reduce system efficiency and affect electrolyzer durability.

Another significant limitation is the high capital cost of electrolysis systems. Electrolyzers require advanced materials, such as catalysts, membranes, and specialized components, which increase the overall system cost. For example, proton exchange membrane (PEM) electrolyzers use noble metal catalysts such as platinum and iridium, which are expensive and limited in availability. Consequently, the production cost of green hydrogen remains higher than that of conventional hydrogen produced using fossil-fuel-based technologies.

Water quality requirements also present challenges for electrolysis-based hydrogen production systems. Most commercial electrolyzers require highly purified or deionized water to ensure efficient electrochemical reactions and to prevent electrode corrosion. The use of alternative water sources, such as wastewater or seawater, introduces additional complications due to impurities, dissolved salts, and organic contaminants. These impurities can cause electrode scaling, membrane fouling and reduced hydrogen production efficiency.

In wastewater-based hydrogen production systems, variations in wastewater composition represent another technical challenge. Industrial and municipal wastewater streams often contain fluctuating concentrations of organic matter, heavy metals, and suspended solids. These variations can influence electrochemical reactions and affect the long-term stability of the electrolysis systems. Therefore, suitable pretreatment technologies are often required before wastewater can be used in electrolysis.

Hydrogen storage and transportation also pose significant challenges to the development of a hydrogen-based energy economy. Hydrogen has a low volumetric energy density under ambient conditions, making storage and transportation difficult. Technologies such as compressed hydrogen storage, liquid hydrogen storage, and chemical storage methods require additional infrastructure and energy consumption, increasing the overall cost of hydrogen supply chains.

Furthermore, the development of large-scale hydrogen infrastructure requires substantial investments in pipelines, storage facilities, refuelling stations, and distribution networks. Establishing such infrastructure will require strong policy support, technological innovation, and collaboration between governments, industries, and research institutions.

Despite these challenges, ongoing research efforts are focused on improving electrolyzer efficiency, developing cost-effective catalyst materials, enhancing membrane durability, and integrating renewable energy systems with hydrogen production technologies. Continued advancements in materials science, system design, and energy infrastructure are expected to significantly improve the feasibility and economic competitiveness of renewable hydrogen production in the future.

Research Gap

Although significant research has been conducted on hydrogen production technologies and renewable energy integration, several limitations remain in the current literature. Most existing hydrogen production methods are dominated by fossil fuel-based technologies, such as steam methane

reforming and coal gasification, which contribute substantially to greenhouse gas emissions and environmental pollution. Therefore, recent studies have increasingly focused on renewable energy-powered electrolysis systems for sustainable hydrogen production.

Several researchers have investigated hydrogen production through water electrolysis using renewable energy sources, such as solar and wind energy. These studies mainly focus on improving electrolyzer efficiency, developing advanced catalysts, and optimizing system integration with renewable power sources. Solar photovoltaic-powered electrolysis systems have demonstrated promising potential for producing green hydrogen with reduced carbon emissions. However, many of these studies primarily emphasize energy efficiency improvements while giving limited attention to the sustainability of the water resources used for electrolysis.

Another important research area involves the use of alternative water sources, such as seawater, industrial wastewater, and treated municipal wastewater, for hydrogen production. Previous studies have explored wastewater electrolysis and microbial electrolysis systems to simultaneously treat wastewater and generate hydrogen. These approaches demonstrate the potential for integrating wastewater management with renewable energy production.

Despite these developments, most existing studies have focused primarily on industrial wastewater, municipal wastewater, or seawater electrolysis. Very limited research has been conducted on the utilization of air-conditioning condensate water as a feedwater source for hydrogen production. Air-conditioner condensate water is widely generated in residential, commercial, and institutional buildings, especially in regions with high cooling demand. Condensate water represents a promising yet underutilized water resource for electrolysis-based hydrogen production systems owing to its relatively low total dissolved solids (TDS) and higher purity than other wastewater sources.

Furthermore, existing research on wastewater-based hydrogen production often focuses on biological or conventional electrochemical processes, while relatively few studies have investigated the physicochemical properties and electrochemical suitability of condensate water from air conditioners for hydrogen generation. Understanding parameters such as pH, conductivity, mineral content, and total dissolved solids is essential for evaluating the feasibility of seawater as a feedwater source in electrolysis systems.

In addition, there is limited research on the integration of renewable energy-powered electrolysis systems with condensate water recovery from air-conditioning systems. Although solar-powered hydrogen production has been widely studied, the combined use of solar energy and air conditioner condensate water for decentralized hydrogen generation in buildings remains largely unexplored.

Therefore, a clear research gap exists in investigating the potential of air-conditioner condensate wastewater as an alternative feedwater source for green hydrogen production using renewable energy-powered electrolysis systems. Addressing this gap can contribute to reducing freshwater consumption, improving wastewater utilization, and enhancing the sustainability of hydrogen production technologies.

FUTURE SCOPE

The rapid development of renewable energy technologies and electrochemical systems has created significant opportunities for the sustainable production of hydrogen. However, further research and technological advancements are required to improve the efficiency, economic feasibility, and large-scale implementation of green hydrogen production systems. Future research should focus on improving electrolysis technologies, integrating renewable energy systems, and exploring alternative water resources for sustainable hydrogen generation.

An important research direction involves the development of advanced electrolyzer technologies with higher efficiency and durability. Current electrolysis systems, such as alkaline water electrolysis and

proton exchange membrane electrolysis, rely on expensive catalysts and membrane materials, which increase system costs. Future studies should focus on developing cost-effective catalyst materials, improving membrane stability, and optimizing electrolyzer designs to enhance hydrogen production efficiency while reducing operational costs.

Hybrid systems can reduce the intermittency associated with renewable energy sources and improve the overall reliability of hydrogen production.

Conventional electrolysis systems require highly purified water, which may limit large-scale hydrogen production in regions with freshwater scarcity. Therefore, further studies should investigate the feasibility of using different alternative water sources, such as seawater, treated municipal wastewater, industrial wastewater, and air-conditioner condensate water, for hydrogen production.

Air-conditioner condensate water presents significant potential for decentralized hydrogen production in urban environments. Future research should focus on evaluating the potential for condensate water generation in buildings, developing efficient collection systems, and studying the physicochemical characteristics of condensate water to determine its suitability for electrolysis-based hydrogen production.

Another important research direction involves the development of integrated energy–water systems that combine renewable energy generation, wastewater treatment, and hydrogen production. Such integrated systems can simultaneously address energy and water challenges by converting wastewater into a valuable energy resource. Solar-powered electrochemical wastewater treatment systems, for example, have demonstrated the potential to remove pollutants while generating hydrogen as a byproduct.

Furthermore, techno-economic analysis and life-cycle assessment studies are required to evaluate the environmental and economic feasibility of renewable hydrogen production technology. These analyses can help identify the most sustainable and cost-effective hydrogen production pathways for large-scale deployment.

Overall, future research should focus on integrating renewable energy technologies, alternative water resources, and advanced electrolysis systems to develop sustainable and economically viable hydrogen production technologies. Continued innovation in materials science, system integration, and energy infrastructure will play a crucial role in enabling the widespread adoption of green hydrogen as a clean energy carrier.

CONCLUSION

The increasing global demand for clean and sustainable energy has intensified research efforts toward alternative energy carriers, such as hydrogen. Conventional hydrogen production methods, which are primarily based on fossil fuels, contribute significantly to greenhouse gas emissions and the degradation of the environment. Therefore, the development of environmentally friendly hydrogen production technologies has become a priority for achieving global energy sustainability.

Among the available hydrogen generation methods, water electrolysis using renewable energy has gained strong recognition as a promising approach for producing green hydrogen. When powered by electricity from solar and wind sources, electrolysis supports hydrogen production in a manner that avoids direct carbon emission. This approach supports the transition toward a low-carbon energy system and helps to reduce dependence on fossil fuels.

However, large-scale hydrogen production through electrolysis requires significant quantities of purified water, raising concerns regarding freshwater availability and resource sustainability.

Consequently, the exploration of alternative water resources has become an important area of research in sustainable hydrogen production systems. Wastewater resources, such as industrial wastewater, treated municipal wastewater, and seawater, have been investigated as potential feedwater sources for electrolysis processes.

In this context, air-conditioner condensate water is a relatively clean and underutilized water resource that can potentially be used for hydrogen production. Owing to its low total dissolved solids and relatively high purity, condensate water may serve as a suitable feedwater source for electrolysis-based hydrogen generation systems with minimal pretreatment requirements. In regions with high cooling demand, large volumes of condensate water are generated daily in buildings, offering significant opportunities for sustainable water reuse in the future.

Overall, the integration of renewable energy systems with electrolysis technologies and alternative water resources can significantly enhance the sustainability of hydrogen production systems. The utilization of air-conditioner condensate water for green hydrogen generation provides a promising pathway for improving water resource efficiency while supporting clean-energy production. Continued research on electrolysis technologies, water quality management, and renewable energy integration is essential for enabling the large-scale implementation of sustainable hydrogen production systems in the future.

REFERENCES

1. Prasanth KP, Pillai RS, Bajaj HC, Jasra RV, Chung HD, Kim TH, et al. Adsorption of hydrogen in nickel and rhodium exchanged zeolite X. *Int J Hydrogen Energy*. 2008;33(2):735-45.
2. Chen Z, Su SI. Photovoltaic supply chain coordination with strategic consumers in China. *Renew Energy*. 2014;68:236-44.
3. Dunn S. Hydrogen futures: toward a sustainable energy system. *Int J Hydrogen Energy*. 2002;27(3):235-64.
4. Glenk G, Reichelstein S. Economics of converting renewable power to hydrogen. *Nat Energy*. 2019;4(3):216-22.
5. Abdullah MA, Mursalin R. Condensed water recycling in an air conditioning unit. *IOSR J Mech Civ Eng*. 2021;18(3):13-19.
6. Ivy J. Summary of electrolytic hydrogen production: milestone completion report. Golden (CO): National Renewable Energy Laboratory; 2004 Mar 31.
7. Mudgal A, Hadia NJ. Green hydrogen production: synergizing efficient water desalination and food crop by products. *Environ Sci Pollut Res Int*. 2025;32(54):30246-62.
8. Kumar R, Chakraborty P, Singh PK, Chakraborty S, Tripathy SK, Saratale GD, et al. Emerging approaches on biomass and water-based hydrogen production and downstream recovery pathways: a review on recent challenges and prospects. *Rev Environ Sci Biotechnol*. 2025;24(4):957-1018.
9. Kumar R, Sharma A, Kumar P, KS K, Albert HM, Agrawal AP, et al. Advanced materials and system innovations for seawater electrolysis in hybrid renewable energy systems: toward sustainable hydrogen production. *Chem Phys Impact*. 2025:100972.
10. Turner JA. Sustainable hydrogen production. *Science*. 2004;305(5686):972-4.
11. Baykara SZ. Hydrogen production by direct solar thermal decomposition of water, possibilities for improvement of process efficiency. *Int J Hydrogen Energy*. 2004;29(14):1451-8.
12. Ursúa A, Sanchis P, Marroyo L. Electric conditioning and efficiency of hydrogen production systems and their... In: *Renewable Hydrogen Technologies: Production, Purification, Storage, Applications and Safety*. 2013. p. 333.
13. Ursua A, Gandia LM, Sanchis P. Hydrogen production from water electrolysis: current status and future trends. *Proc IEEE*. 2011;100(2):410-26.
14. Bajpai P, Dash V. Hybrid renewable energy systems for power generation in stand-alone applications: a review. *Renew Sustain Energy Rev*. 2012;16(5):2926-39.
15. Zeng K, Zhang D. Recent progress in alkaline water electrolysis for hydrogen production and applications. *Prog Energy Combust Sci*. 2010;36(3):307-26.

16. Benghanem M, Mellit A, Almohamadi H, Haddad S, Chettibi N, Alanazi AM, et al. Hydrogen production methods based on solar and wind energy: a review. *Energies*. 2023;16(2):757.
17. Badruzzaman A, Karagoz S, Eljack F. Sustainable-green hydrogen production through integrating electrolysis, water treatment and solar energy. *Front Chem Eng*. 2025;7:1526331.
18. Farhani S, Alharbi SS, Alharbi SS, Barhoumi EM, Bacha F. Investigation and analysis of solar and wind energy potential for green hydrogen production via alkaline water electrolysis. *IEEE Access*. 2025.
19. Barghash H, AlRashdi Z, Okedu KE, Hasoon FN. Assessing environmental benefits of green hydrogen production from sewage treatment plants considering solar PV PEM electrolysis. *Results Eng*. 2025;26:105559.
20. Ismail M, Kandeal AW, Sharshir SW, Abd EL-Gawaad NS, Al Bahir A, Nasser M. Green hydrogen-powered air conditioning system for hot climates: performance and economic analysis. *Energy Build*. 2025;337:115697.
21. Han JH, Bae J, Lim J, Jwa E, Nam JY, Hwang KS, et al. Acidification-based direct electrolysis of treated wastewater for hydrogen production and water reuse. *Heliyon*. 2023;9(10).
22. Baía A, Arroyo-Escoto AI, Ramos N, Abdelkarim B, Pereira M, Fernandes MC, et al. Hydrogen production from winery wastewater through a dual-chamber microbial electrolysis cell. *Energies*. 2025;18(12):3043.
23. Boutarbouch M, El-Moustaqim K, Azoulay K, Boudoudou D, Abarkan A, Moufti A, et al. Solar-powered electrochemical processes for sustainable wastewater treatment and green hydrogen production: a review. In: *BIO Web of Conferences*. Vol. 215. EDP Sciences; 2026. p. 04009.
24. Carmo M, Fritz DL, Mergel J, Stolten D. A comprehensive review on PEM water electrolysis. *Int J Hydrogen Energy*. 2013;38(12):4901-34.
25. Walter MG, Warren EL, McKone JR, Boettcher SW, Mi Q, Santori EA, et al. Solar water splitting cells. *Chem Rev*. 2010;110(11):6446-73.
26. Miguel EVS, Pamela CR. Genetic and biotechnological approaches for biofuel crop improvement. *Curr Opin Biotechnol*. 2010;21(2).
27. Logan BE, Call D, Cheng S, Hamelers HV, Sleutels TH, Jeremiasse AW, et al. Microbial electrolysis cells for high yield hydrogen gas production from organic matter. *Environ Sci Technol*. 2008;42(23):8630-40.
28. Logan BE, Rabaey K. Conversion of wastes into bioelectricity and chemicals by using microbial electrochemical technologies. *Science*. 2012;337(6095):686-90.
29. Wang J, Wan W. Comparison of different pretreatment methods for enriching hydrogen-producing bacteria from digested sludge. *Int J Hydrogen Energy*. 2008;33(12):2934-41.
30. Kumar SS, Himabindu V. Hydrogen production by PEM water electrolysis—a review. *Mater Sci Energy Technol*. 2019;2(3):442-54.
31. Ali MA, Saifur S, Ali MA. Quantification of condensate water generated from air conditioning system. *Glob Sci Technol J*. 2018;6(3):44-56.
32. Ahmed HM. Air conditioning condensate: a potential water source for irrigation. In: *Business Sustainability with Artificial Intelligence (AI): Challenges and Opportunities*. Vol 1. Cham: Springer Nature Switzerland; 2024. p. 1213-23.
33. Pandey AK. Sustainable water management through integrated technologies and circular resource recovery. *Environ Sci Water Res Technol*. 2025;11(8):1822-46.
34. Chakraborty P, Abhishek S, Sethi C, Jeevan G. Condensate water as alternate resource for mitigating water stress: a case study. *Water Conserv Sci Eng*. 2025;10(1):4.
35. Song Q, Chen X, Liu J, Chen J, Loo KH. Decentralized energy management of renewable hydrogen production systems without communication networks. *IEEE Trans Ind Electron*. 2023;71(8):8927-37.
36. Momirlan M, Veziroglu TN. The properties of hydrogen as fuel tomorrow in sustainable energy system for a cleaner planet. *Int J Hydrogen Energy*. 2005;30(7):795-802.
37. Real SG, Ortiz MG, Castro EB, Visintin A. The discharge process of nickel hydroxide electrodes used in batteries: a dynamic analysis study by EIS. *Int J Hydrogen Energy*. 2008;33(13):3493-5.

38. Ust'ak S, Havrland B, Muñoz JO, Fernández EC, Lachman J. Experimental verification of various methods for biological hydrogen production. *Int J Hydrogen Energy*. 2007;32(12):1736-41.
39. Xu H, Li J, Xu J, Wang J, Deng F, Li J, et al. Synthesis and properties of a zeolite LEV analogue from the system—Na₂O–Al₂O₃–SiO₂–N,N-dimethylpiperidine chloride–H₂O. *Catal Today*. 2009;148(1-2):6-11.
40. Staffell I, Scamman D, Abad AV, Balcombe P, Dodds PE, Ekins P, et al. The role of hydrogen and fuel cells in the global energy system. *Energy Environ Sci*. 2019;12(2):463-91.