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Original Research Article

Future potential and existing state of green hydrogen energy production

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ABSTRACT
Green hydrogen production is the process of creating hydrogen using sustainable and renewable energy sources. Thus, by using this method, greenhouse gas emissions will be reduced and our dependency on fossil fuels will decrease, making hydrogen a clean and sustainable energy source. The main advantage of using green energy to produce green hydrogen is that no hazardous pollutants or greenhouse gases are released throughout the process. Therefore, it is essential to take into account the whole hydrogen supply chain, including storage, transportation, and end consumers, in order to ensure all of the environmental benefits. A promising sustainable energy source, hydrogen aims to achieve net-zero emissions and decarbonization by 2050. The methods for producing green hydrogen that are essential for a sustainable energy future and a clean environment have been emphasized in this research. It also provides a synopsis of the background, prospects, and energy-related aspects of green hydrogen production. As a result, this viewpoint offers fresh perspectives and avenues for future investigation to hasten the advancement and pinpoint the possibilities of green hydrogen generation.

1. Introduction

In the current global decarbonization movement, one technique that is being considered more and more as a means of reducing greenhouse gas (GHG) emissions and environmental degradation is the technology of producing green hydrogen from renewable energy sources [1, 2]. But society is realizing that fossil fuels are not carbon-free, which prompts serious consideration of other options.

To achieve the objectives of the Paris Agreement, the world's energy system must fundamentally shift from one that is mostly dependent on fossil fuels to one that is efficient, sustainable, and emits little carbon dioxide. As a result, a reduction in global CO_2 emissions of more than 90% is needed, and renewable energy is expected to directly contribute 41% of this reduction [3, 4]. An affordable and sustainable substitute for energy storage and consumption is hydrogen (H_2) [5, 6]. Furthermore, it has the potential to significantly increase the percentage of hydrogen and help realize a low-carbon civilization [7].

Since the COVID-19 epidemic, hydrogen technologies have been viewed as a means of bolstering a number of economic sectors. A significant consensus currently exists on hydrogen's potential, in part because of an increasingly aggressive climate policy [8, 9]. Hydrogen's potential for decarbonization is further demonstrated by the fact that it may be utilized in fuel cell technology for a variety of industries and applications, including transportation, industry, and residential [10–12].

The development of hydrogen as a zero-carbon fuel is gaining exceptional political and commercial impetus, as evidenced by the numerous initiatives and projects that are quickly expanding throughout the world. The growing increase is a result of the pressing need to cut greenhouse gas emissions as well as the falling cost of hydrogen produced from renewable energy sources, or "green hydrogen" [3, 13]. But during the coming decades, it is anticipated that green hydrogen will gain significant traction and achieve high economic viability [13, 14]. Green hydrogen production is one of the methods for producing hydrogen; other methods include using coal, methane, bioenergy, and even solar energy [15, 16].

Many nations view hydrogen as the energy management solution of the future, and they are becoming more in favor of using hydrogen technology aimed at achieving a decarbonized economy. As a result, numerous methods and tactics for creating and using hydrogen have been developed [17].

Anouti et al. [18] estimate that the global demand for green hydrogen—that is, hydrogen produced with fewer carbon dioxide emissions—could reach 530 million tonnes (Mt) by 2050. As a result, it would replace about 10.4 billion barrels of oil, or about 37% of the world's oil production prior to the pandemic [18, 19]. It projects that by 2050, the global market for green hydrogen exports might be valued at $300 billion, supporting the employment of about 400 000 people in the hydrogen and renewable energy sectors [18].

The color tones of hydrogen, which include blue, grey, brown, black, and green, are determined by the method of production, the energy source utilized, and the impact on the environment [20]. Grey hydrogen is recovered from natural gas via the steam-reforming/auto-thermal reforming process, however as a byproduct, CO_2 is released into the environment. Blue hydrogen is produced when natural gas is converted to hydrogen via the steam-reforming process while capturing CO_2 emissions. Brown hydrogen is the most common type of hydrogen utilized today. It is mostly created by gasifying fuel that is rich in hydrocarbons, which releases CO_2 into the atmosphere as a byproduct. On the other hand, water electrolysis, which is driven by renewable energy sources, produces green hydrogen [18, 21, 22].

Based on the sustainable development strategy fully endorsed by UN Member States, green hydrogen is already competitive in areas with all the necessary requirements [15] and will be crucial to meeting the Sustainable Development Goals (SDGs) for the UN 2030. "Affordable and Clean Energy" is essential to the SDG 7 part in question [23, 24]. This is the reason that in recent years, numerous efforts have been made worldwide to achieve this goal.

Thus, building on the points raised in the introduction, we examine green hydrogen production technologies in this study and explore several facets of the significance of the expansion of the green hydrogen economy (GEE). This study's main goal is to demonstrate the green hydrogen generation process's potential, advancement, and importance in supplying the energy needed. The structure of the paper is as follows. The introduction is summed up in Section 1, the energy transition with green hydrogen is analyzed in Section 2, the general overview of green hydrogen production is covered in Section 3, the perspective on green hydrogen energy production is covered in Section 4, and the conclusions and suggestions for further research are summarized in Section 5.

2. Overview of green hydrogen production

Hydrogen has numerous applications, such as fuel for fuel cell vehicles, power generation, energy storage, and industrial production. Consequently, as the world works to transition to a low-carbon economy, the production of hydrogen from renewable energy sources is crucial to achieving sustainable energy targets (SETs).

Water and renewable energy resources are needed in vast quantities for the creation of green hydrogen. Therefore, it has been shown that the best places to produce massive amounts of green hydrogen are those that have an abundance of renewable energy resources and are also easily accessible to water supplies. However, technological advancements and cost reductions are needed for green hydrogen to become a more economically viable alternative to fossil fuels.

Information needs to be established at the government level in order to meet the goal of increasing the production and use of green hydrogen. They can help with adoption in two ways: by boosting production and ensuring a continuous supply of renewable energy; and by creating an infrastructure for storing and transporting hydrogen and raising the demand for green hydrogen and its derivatives [25].

3. Energy transition with green hydrogen

Green hydrogen technology has the potential to be extremely important for energy storage. Hydrogen can be produced by electrolysis by employing excess renewable energy generated during periods of low demand. Hydrogen can be stored and then converted back into power using fuel cells, or it can be used immediately in a variety of applications when needed. Since there are various ways to store hydrogen, including as a liquid, gaseous fuel, or solid state, the best technique to store it depends on how it will be used or exported. This makes it feasible to include renewable energy sources like solar and wind power into the system. This could reduce the hydrogen yield's overall cost.

A few businesses that stand to gain from the decarbonization of clean hydrogen generated from renewable energy sources, fossil fuels, nuclear power, or carbon capture are iron and steel, long-distance transportation, and chemicals. It has been challenging for these industries to cut their emissions. Automobiles powered by hydrogen would improve air quality and energy security. Hydrogen can help integrate different renewable energy sources into the electrical grid, despite being one of the few alternative energy sources that can store energy for days, weeks, or months.

Both surface and subterranean hydrogen storage technologies are more dependable and effective when used; large-scale storage also provides benefits for the energy system's flexibility and energy demand [26]. For many uses, including transportation and industrial processes, the efficient and secure storage of hydrogen is a critical factor.

The shift to green hydrogen will open up new job opportunities in a number of industries, including infrastructure, manufacturing, fuel cells, and electrolyser operation and maintenance. Furthermore, the rise of the green hydrogen industry has the potential to stimulate economic expansion, generate revenue from exports, attract investments, and spur scientific advancements in the field.

Current research and development efforts are concentrated on green hydrogen technology advancement. Therefore, this includes improving the efficiency of electrolysis processes, developing fuel cells at a reasonable cost, researching novel materials for hydrogen storage, and increasing the overall effectiveness of hydrogen systems. Since technology advances, there will be more uses for green hydrogen since it will be more affordable, more efficient, and more widely available. The development of state-of-the-art electrolyser devices is predicated on lowering manufacturing costs, improving efficiency, and expanding the role that electrolysis plays in the worldwide hydrogen economy.

But a number of objectives need to be met before global hydrogen trade is a viable, cost-effective choice on a big scale. The secret is a techno-economic analysis that looks at the conditions necessary for commerce of this kind to be profitable. The scenarios project the outlook for the hydrogen trade through 2050, when access to hydrogen production and transportation prices is possible. It is anticipated that the trade of hydrogen would grow significantly in local marketplaces.

Approximately half of the hydrogen traded globally by 2050 will be carried through pipelines, according to a global plan outlined in the 1.5°C scenario as a "pathway toward decarbonization and net-zero emissions via 2050." Most of the hydrogen network would be based on existing natural gas pipes that can be converted to carry pure hydrogen, significantly reducing transportation costs [27, 28]. As a result, we can assess the outlook for the global hydrogen trade in 2030 and 2050 by looking at the economic and technological capacity of green hydrogen generation globally over a range of scenarios [27].

Understanding the potential of hydrogen as a sustainable and clean energy carrier requires advancement and supply chain optimization. Furthermore, by creating a labor market, socioeconomic factors can be extended to the supply chain through the installation or deployment of renewable energy equipment. Therefore, it is expected that the hydrogen supply chain will contribute significantly to the transition to a low-carbon energy system as infrastructure and technology advance.

Additional perspectives on green hydrogen to broaden understanding encompass outreach strategies that integrate hydrogen-related subjects into the curriculum, such as community workshops, internet resources, and partnerships with academic establishments.

As a result, a variety of reasons have encouraged several nations to support the adoption of green hydrogen technology projects. These seek to lower greenhouse gas emissions and establish a decarbonized economy, with hydrogen being taken into consideration as a substitute for sustainable energy management. The breakdown of newly announced ongoing investment initiatives in the production of green hydrogen is presented in Table 1.

Achieving the 1.5°C scenario necessitates the development of large-scale, commercially feasible hydrogen production and commerce. The amount of electricity required to produce hydrogen must be sufficient and should not interfere with the supply of electricity required for other essential and productive uses. As a result, the growth of renewable energy, which is the foundation of the switch to green hydrogen, is accelerated and expanded.

Table 1: List of major planned and ongoing green hydrogen initiatives.

Name of project	Country	Estimated cost	Estimated capacity of green hydrogen harvesting	References
NEOM	Saudi Arabia	$8.5 billion	1.2 M tones/year	[30]
Asian Renewable Energy Hub	Australia	-----	1.75 M tones/year	[31]
Green Energy Oman	Oman	$10 billion	3.75 M tones/year	[31]
Reckaz	Kazakshtan	$40-50 billion	3 M tones/year	[31]
HyDeal Ambition	Spain	-----	3.6 M tones/year	[31]
Western Green Energy Hub	Australia	$70 billion	20 M tones/year	[31]
Hy deal Ambition	West Europe	-----	3.6 M tomes/year	[31]
Sinopec	China	¥ 2.6 billion	3.5 M tones/year	[32]
-----	India	$4.29 billion	5 M tones/year	[33]

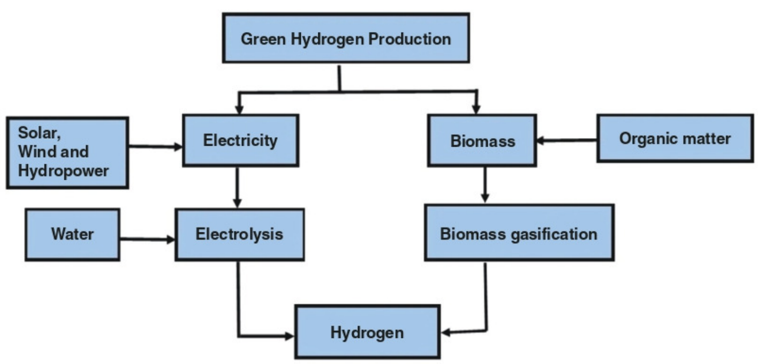

Figure 1: Possible route for generating hydrogen using renewable energy.

When costs come down, technology advances, and policies that support it are implemented, green hydrogen has the potential to be a key component of a future energy system that is cleaner and more sustainable [34]. A possible process for creating hydrogen from renewable energy sources is shown in Figure 1. When organic matter, such as food scraps and animal manure, decomposes, biogas, an environmentally benign renewable energy source, is created. In a controlled environment, organic materials or agricultural waste can be gasified for biomass gasification to produce a variety of hydrogen. The generated biogas can be used to power vehicles, heat homes, and produce electricity.

By using electrolysers and electricity generated by renewable energy sources like solar technology, photovoltaic (PV), concentrated solar power (CSP), wind, or hydropower, electrolysis is a process that turns water into hydrogen and oxygen. After produced, the hydrogen can be stored or used for a variety of applications, including industrial processes and fuel cells. Using electricity to separate molecules in water into hydrogen and oxygen is the basic method of producing hydrogen by electrolysis, as follows:

$$H_2O + \text{energy} \rightarrow H_2 + 12O_2 \quad (1)$$

The utilization of solar radiation to directly drive the water-splitting process is a crucial aspect of another method, known as the photo-electro-chemical (PEC) hydrogen generation technology [35, 36]. PEC cells convert solar energy into hydrogen. While this technology is still in its early stages, it shows promise for efficiently and sustainably manufacturing hydrogen [35].

Algae have been suggested as a viable resource for the generation of green hydrogen due to their capacity for photosynthetic oxygen synthesis. Under specific circumstances, some species of algae can also produce "hydrogen gas as a by-product of their metabolism." The bio-hydrogen production process, which is a topic of interest and ongoing research [37, 38], is the foundation for green hydrogen production from algae, however it is not yet widely employed in industrial practice [39–41].

In order to minimize the cost of creating hydrogen, electrolysers should operate at a greater utilization rate; however, this is incompatible with the limited supply of restricted energy [42]. Direct saltwater electrolysis as a means of generating hydrogen and oxygen has been proposed in a number of research publications [43–45].

Table 2: Regional breakdown of the potential for global production of green hydrogen [46].

Region	Estimated energy capacity, Exajoule (EJ)	Percentage value
Sub-Saharan Africa	2715	28.6
Middle East and North Africa	2023	21.3
North America	1314	13.8
Oceania (Australia)	1272	13.4
South America	1114	11.7
Rest of Asia	684	7.2
Northeast Asia	212	2.23
Europe	88	0.92
Southeast Asia	64	0.67

4. Prospective of green hydrogen energy

Green hydrogen is a clean energy source that requires cooperation from businesses, governments, communities, and academic organizations. It presents an opportunity to boost sustainable growth, diversify energy sources, and cut greenhouse gas emissions [14]. Table 2 lists the potential and capability for producing green hydrogen globally, broken down by continent-specific location. Sub-Saharan Africa has the highest potential at around 28.6%, followed by the Middle East and North Africa at approximately 21.3%. The remaining areas of the continent are then mentioned as follows.

From an economic standpoint, green hydrogen is a significant opportunity. It has the capacity to encourage the development of new industries, the generation of job opportunities, and economic progress. Green hydrogen generation can therefore be used by nations with an abundance of renewable energy resources to export energy, diversify their economies, and reduce their reliance on fossil fuels.

Reducing systems that require a substantial quantity of variable energy from renewable sources can be aided by the creation of hydrogen [42]. From the standpoint of technological progress, green hydrogen is regarded as a catalyst for technological advancement in this context. It is anticipated that research and development efforts aimed at improving materials and techniques, lowering expenses, and raising electrolysis efficiency would lead to technological advancements in the industry. This viewpoint emphasizes the innovative possibilities and advancements in green hydrogen technology.

Furthermore, green hydrogen is seen as a crucial catalyst for the energy transition from that point of view. As a result, renewable energy sources can be integrated and balanced with the help of clean energy sources like solar and wind power. Because green hydrogen offers grid flexibility and long-term energy storage, it may raise the proportion of clean energy sources in the energy system.

Based on various countries' carbon-neutrality targets and energy transition strategies, it is evident that the global transition is moving more quickly [47]. Green hydrogen initiatives are getting more and more funding from throughout the world, including the USA, Saudi Arabia, China, Germany, and Austria, to mention a few. These nations have made progress in putting large-scale green hydrogen projects into action [15, 42].

Hydrogen energy has multiple applications in the domains of industry, electricity, building, transportation, etc. [47]. The schematic flow of viewpoints on green hydrogen production is explained in Figure 2. Since more recent sources have become the latest insights on its current state and projections, the need for green hydrogen has changed recently. In the upcoming years, as green technology advance and the necessity of combating climate change develop, it is expected that the need for green hydrogen will expand. Demand is also required for decarbonization, regulatory support, technological advancements, and environmental factors of mitigating climate change.

According to a study, because hydrogen can cut CO_2 emissions by about 80 GT (gigatonnes) by 2050, it has a substantial potential to help the world fulfill decarbonization goals/net-zero emissions by that same year and keep global warming to 1.5°C [48].

Rich natural resources and a favorable geographic location are prerequisites for green hydrogen potential. Water, solar, wind, and hydro energy, as well as biological materials, are therefore available. Widespread implementation of green hydrogen is made possible by infrastructure development, and significant infrastructure advancement is necessary. It entails setting up hydrogen filling stations and constructing electrolysis facilities, storage systems, etc.

Additionally, investment projects would be feasible in arid regions, where sizable projects utilizing solar PV and CSP for electricity generation might be built. Electricity can then be utilized to create enough hydrogen for the regional market and export the extra. As a result, these will support the long-term economic growth of nations with significant solar radiation potential.

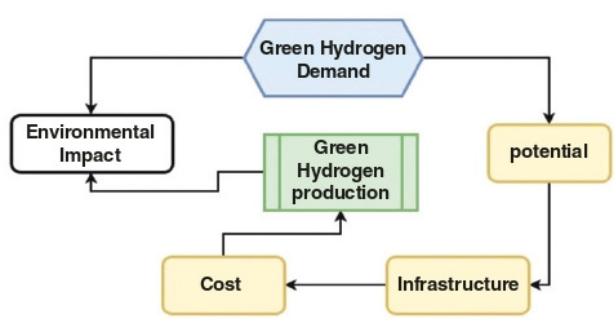

Figure 2: Views on the creation of green hydrogen.

Overall costs will continue to decline due to the economies of scale made possible by a growing worldwide market for green hydrogen and clean energy sources [29]. However, concentrating on supporting the early stages of the expansion of green hydrogen generation during the time when the investment is made will be the most cost-effective approach to employ green finance [49]. When designing a hydrogen plant, the first factor to be taken into account is the investment cost. Low-levelized energy prices from renewable energy resources and electrolysers are therefore a key desirable characteristic. These will increase the project's viability, effectiveness, and affordability for the creation of green hydrogen. One important instrument for achieving global climate targets is the environmental impact of green hydrogen generation, which has the ability to ensure a future for our world that is more environmentally friendly and sustainable.

5. Conclusions

The overview of green hydrogen, its potential, and its contribution to net-zero emissions are outlined in this paper. Therefore, its perspective offers fresh perspectives to quicken the growth of green hydrogen generation initiatives. Scholars, businesses, and governments from all over the world will fund the technology's development in order to hasten the use of green hydrogen. It is regarded as a workable solution for reducing greenhouse gas emissions, promoting energy independence, and assisting in the transition to a low-carbon, ecologically friendly energy system.

For the purpose of meeting energy needs, hydrogen technology has advanced dramatically. As a result of lower costs, green hydrogen yield—which is dependent on renewable energy sources—has lately grown in appeal. As a result, it may help to reduce environmental problems, encourage economic growth, and aid in the global transition to clean and sustainable energy systems. Achieving the full potential of green hydrogen requires overcoming obstacles such as reduced costs, infrastructural development, and industrial scale.

It is possible that a global market for green hydrogen may develop, allowing assignees with an abundance of renewable resources to export excess electricity as hydrogen. Consequently, this could help nations transition to a more sustainable energy mix and lessen their reliance on the import of fossil fuels. Future research will focus on creating and thoroughly analyzing an efficient, high-cost electrolyser that will lower the overall cost of green hydrogen production.

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