The current state and future prospects of green energy generation from green hydrogen

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Abstract. Green hydrogen, made by electrolysis of water driven by renewable energy resources, is being considered to be a crucial factor to help achieve deep decarbonization of energy systems as well as industries that are difficult to discuss. This article offers a thorough and comprehensive review of green hydrogen technology that examine their fundamental concepts as well as production routes and their current levels of maturation. The article outlines the differences between the conventional hydrogen production processes that are still heavily driven by fossil fuels and the emergence of low-carbon alternatives that rely upon renewable energy. Special attention is paid to electrolysis techniques, such as proton exchange membranes, alkaline as well as high-temperature systems and also to other methods in the process of development, including photoelectrochemical conversion and biomass conversion. The state of the global green hydrogen sector is investigated through large-scale projects, which reveal an explosive growth in capacity due to favorable renewable sources including solar and wind energy. Despite this rapid expansion, many challenges remain including the cost of production infrastructure needs, intermittent availability of renewable energy sources, and regulatory limitations. The paper wraps up by discussing future developments prospects and highlighting the crucial role played by green hydrogen to support the carbon neutrality goals and energy security as well as the shift towards the sustainable and sustainable low-carbon economy.

Keywords. Green hydrogen; Water electrolysis; Renewable energy integration; Decarbonization; Energy transition

1. Introduction

In a world dominated by the urgency of climate change and the shift to renewable energy sources that are low in carbon hydrogen can be seen as an obvious energy source to cut greenhouse gas emissions and helping to ensure a prosperous future [1]. However, the present production of hydrogen is still primarily based on fossil fuels, employing techniques like gasification, steam reforming or natural gas steam re-molding which make up around 95% of the world's production [2]. While these techniques are extensively used because of their technical maturity however, they also generate substantial carbon dioxide emissions, which contribute to global warming, and putting into question their long-term viability [3]. To address these issues green hydrogen, derived from renewable sources via electrolysis of water powered by wind, solar or hydropower or biomass energy, is emerging as an attractive green alternative[4]. Despite the high price and the current state of development, the technology is an essential tool to cut carbon emissions from the energy industry [5]. Presently, the generation of green hydrogen from sustainable energy sources has been being acknowledged as a viable option to reduce the greenhouse gas (GHG) pollution and environmental pollution, thereby in line with the process of decarbonization of the world. But the public is increasingly conscious that fossil fuels have not been decarbonized, which prompts greater consideration of alternative solutions [6]. Green hydrogen is an economic viable, and eco sustainable alternative to storage and energy consumption. Furthermore, it could help to create an environmentally friendly society and increase the proportion of hydrogen in sustainable energy sources [7]. Numerous initiatives and projects are increasing in popularity across the globe, demonstrating the powerful commercial and political energy behind the growth of hydrogen into a zero-carbon fuel. The growth in this area is due to the decreasing costs of hydrogen produced using sustainable energy sources often known as "green hydrogen," and also by the need to cut down on carbon dioxide (GHG) emission[8]. Many countries see hydrogen as the energy management solution of the future and are increasingly using hydrogen technology in order to build a carbon-free economy. Thus, a variety of strategies and plans to develop and using hydrogen have been proposed. The paper is arranged around various axes of complementary use to offer an extensive review of the energy production potential using green hydrogen. The paper begins with a definition as well as an explanation of basic concepts of the green hydrogen. It is then followed by a brief overview of current production methods. The chapter also provides a brief overview of the industry globally with a focus on its stage of maturity as well as the degree of application. In addition, the future development possibilities of this industry and its socio-economic and environmental impacts are analyzed and compiled into a clear concluding summary.

2. Foundations and Core Principles of Green Hydrogen Technologies

Most abundant of all elements in our universe hydrogen (H) is the top element on the periodic table. It is the most basic and light element that is composed of one nucleus that contains only one proton and a electron that is a peripheral[9]. Dihydrogen molecules (H2) made up from two hydrogen atoms is often known as "hydrogen". It is this molecule that is the object of chemical exploration and has sparked a lot of interest in the energy industry because of its broad range of uses and potential to store energy. Hydrogen is often associated with different colors depending on its origin, notably white, black, grey, blue, and green. This classification is presented in **Table 1**.

Tableau 1. Classification of the different hydrogen production pathways

Hydrogen type	Production process	Energy source	Main advantages	Limitations	Ref
Green	Water electrolysis	Renewable energy sources (solar, wind, hydropower)	No direct greenhouse gas emissions; sustainable solution	High production costs; intermittency of renewable energy sources	[10]
Blue	Methane reforming with carbon capture and storage (CCS)	Natural gas	Mature technology; reduced emissions compared to grey hydrogen	Dependence on fossil fuels; residual CO_2 emissions; CCS efficiency constraints	[11]
Grey	Methane reforming without CO_2 capture	Natural gas	Low cost; large-scale production	High CO_2 emissions; significant climate impact	[12]
Black/Brown	Coal or lignite gasification	Coal	Low-cost process	Very negative environmental impact; high emissions	[13]
Pink	Water electrolysis	Nuclear electricity	Low carbon emissions; stable production	Dependence on nuclear energy; societal acceptability	[14]
Turquoise	Methane pyrolysis producing solid carbon	Natural gas	Low CO_2 emissions; valorization of solid carbon	Technology under development; high costs	[15]
Yellow	Water electrolysis	Solar energy exclusively	No direct greenhouse gas emissions	Solar intermittency; storage requirements	[16]

3. Main technologies for green hydrogen production

3.1- Steam reforming of fossil fuels (steam methane reforming)

Steam reforming is currently one of the most widely used processes for hydrogen production. It is based on the dissociation of the methane molecule (CH4), the main component of natural gas and rich in hydrogen, through a reaction with steam at high temperature, generally around 900 °C [17]. This process involves two successive reactions leading to the formation of hydrogen (H2) and carbon dioxide (CO2), according to the following overall equation **(1)**:

$$CH4 + 2\ H2O \rightarrow 4\ H2 + CO2 \qquad \textbf{(1)}$$

This process results in significant carbon dioxide emissions, which can, in some cases, be partially captured and stored, although these technologies remain limited in deployment at present. It should also be noted that steam reforming can be applied to biogas, thereby offering a partially renewable alternative within this pathway.

3.2- Water electrolysis

Water electrolysis is a hydrogen production method based on the use of an electric current to dissociate the water molecule into hydrogen and oxygen (O_2)[18], according to the following reaction **(2)**

$$\text{H2O + electricity} \rightarrow \text{H2 + ½ O2 + heat} \qquad \textbf{(2)}$$

This process corresponds to the reverse reaction of that occurring in a fuel cell. When the electricity used is derived from renewable or low-carbon sources, water electrolysis enables the production of hydrogen with a low carbon footprint. Several electrolysis technologies exist, which are mainly distinguished by their operating temperature and the nature of the electrolyte used:

• Low-temperature (< 200 °C) alkaline electrolysis, using an aqueous solution of potassium hydroxide (KOH) or sulfuric acid (H_2SO_4) as the electrolyte

• Low-temperature proton exchange membrane (PEM) electrolysis, based on a solid polymer electrolyte that conducts protons, commonly referred to as PEMFC (Proton Exchange Membrane Fuel Cell)

• High-temperature electrolysis (> 400 °C), using a ceramic membrane that conducts oxygen ions, of the SOFC (Solid Oxide Fuel Cell) type. This technology requires coupling with a high-temperature heat source, such as a concentrating solar system or a next-generation nuclear reactor, in order to benefit from low-cost steam.

3.3- Biomass gasification and pyrolysis

Biomass gasification and pyrolysis, particularly of charcoal, are processes that are still largely at the research and development stage. These methods involve subjecting biomass to very high temperatures, typically between 1,200 °C and 1,500 °C, in order to induce its chemical transformation [19]. The process generates a gaseous mixture mainly composed of hydrogen (H_2) and carbon monoxide (CO), known as synthesis gas (syngas). After purification of this mixture, hydrogen can be recovered for various energy applications

3.4- Other processes under research

In addition to conventional technologies, several innovative hydrogen production processes are currently under investigation (**Figure1**) .These include water photo electrolysis, which relies on the use of photoelectrochemical cells capable of splitting water under the effect of light, as well as the thermochemical decomposition of water at high temperatures (between 800 °C and 1,000 °C), potentially powered by nuclear energy [20], [21], [22]. Furthermore, biological processes involving microorganisms, particularly modified bacteria capable of producing hydrogen under solar radiation, are also being studied.

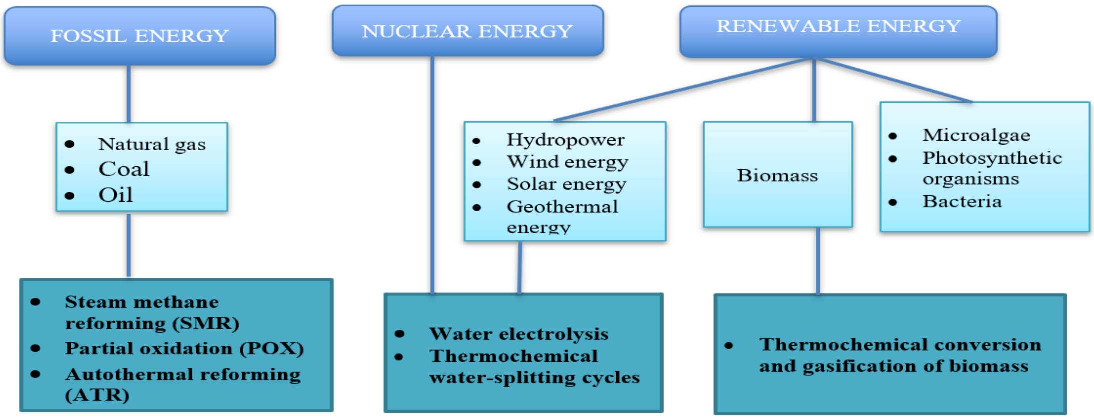

Fig. 1. Main hydrogen production pathways from different energy sources.

4. Current status of the green hydrogen sector

The current situation of the industry is characterized by rapid growth that are reflected in the rise of large-scale developments, but being confronted with economic, technological and regulatory issues which limit its massive deployment. **Table 2** summarizes the most significant global green hydrogen production projects on the gigawatt level, showing the rapid and unimaginable growth of this sector over the last few years[23]. The dramatic growth in the quantity of projects and capacities is a sign of an unwavering commitment from both the political and industrial world toward green hydrogen. This is regarded as an important strategic tool to help in the transition to renewable energy and decarbonization of industries that are not easy to electrify.

Tableau 2. Overview of Major Global Gigawatt-Scale Green Hydrogen Production Projects

Project	**Capacity (GW)**	**Location**	**Energy source**	**Intended use of hydrogen**	**Estimated production**	**Expected completion date**	**Estimated cost**	**Ref**
HyDeal Ambition	67	Europe	Solar	European industry	3.6 Mt H_2/year	Before 2030	-	[24]
Kazakhstan Project	30	Kazakhsta n	Wind + solar	Export / domestic use	3 Mt H_2/year	2024–2027	-	[25]
Western Green Energy Hub	28	Australia	Wind + solar	Export and domestic use	3.5 Mt H_2/year	After 2028	70 G$	[26]
AMAN	18	Mauritani a	Wind + solar	Steel, transport, fertilizers	Not specified	Not specified	-	[27]
Oman Green Hydrogen	14	Oman	Wind + solar	Export	Not specified	2038	~10 G$	[28]
NortH2	10	Netherlan ds	Offshore wind	Heavy industry	1 Mt H_2/year	2040	-	[29]
AquaVentus	10	Germany	Offshore wind	Hydrogen grid	1 Mt H_2/year	2035	-	[30]

Analyzing installed capacities shows a high concentration of projects with very large scales that exceed 10 GW. The largest of these is the European HyDeal Ambition project (67 GW). From the perspective of geography the majority of projects are situated on Europe, Australia, the Middle East, and Latin America regions that have the potential of Renewable energy resources, especially wind and solar. The close-to-systematic connection of

 https://doi.org/10.1051/bioconf/202621504010

electrolyzers and energy sources proves the vital role played by renewable energy sources in the production of hydrogen with low carbon. Offshore wind is also an option that is highly sought-after within Northern Europe, due to its capacity to supply larger-scale and stable power generation. Concerning the intended use green hydrogen is mostly targeted at heavy industries, green ammonia production along with long-distance transport as well as export markets[31]. Ammonia's dominance as a valorization vehicle is attributed to its convenience in storage and transportation, in addition to its significant function in fertilizer production, and its potential as a substitute fuel. Furthermore, certain projects incorporate green hydrogen into energy uses like low-carbon electric power generation or district heating, which highlights the wide range of potential future uses. Despite these optimistic perspectives, the state of the projects shows that the majority are still in an early stage of development, including feasibility studies or pre-engineering phases. The dates for completion typically range between 2025-2040, are indicative of the magnitude of the investment required as well as the technical, economic and regulatory hurdles which need to be tackled. The estimated costs, if available, further demonstrate the importance of capital for these infrastructures.

5. Development prospects of green hydrogen

The shift towards clean energy using green hydrogen necessitates collaboration among industries, governments, communities and research institutions. It offers a chance to increase sustainable growth, diversify sources of energy and decrease emissions of GHGs. Energy from hydrogen can be utilized in numerous fields encompassing industry, electricity, construction, transportation, etc. **Figure 2** elucidates the schematic flow of perspectives on green hydrogen production. The demand for green hydrogen has recently evolved since more recent sources have become the latest insights on its current status and projections. The need for green hydrogen is anticipated to increase over the coming years as green technologies develop and the urgency to battle climate change grows. The demand is also needed for environmental aspects of climate change mitigation, decarbonization, techno- logical developments and policy support. A study reported that hydrogen has a significant potential role in supporting the globe in meeting decarbonization goals/net- zero emissions by 2050 and limiting the global warming phenomenon to 1.5°C because it can reduce ~80 GT of CO_2 emissions by 2050.

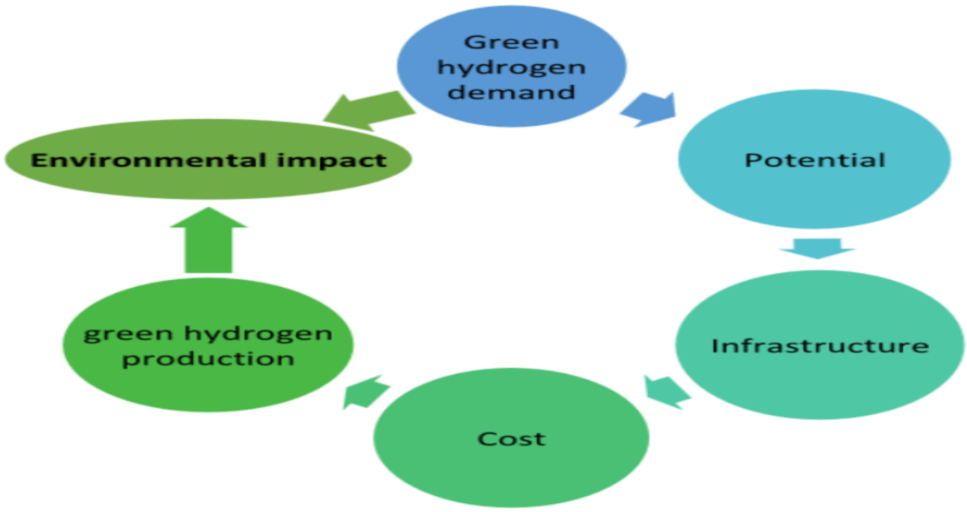

Fig. 2. Perspectives for the development of green hydrogen

6. Conclusion

This chapter has provided an overview of the green hydrogen sector by examining its fundamental principles, current production technologies, associated renewable energy sources, and key energy applications. The analysis of the current state of the sector highlights a strong development dynamic, characterized by the emergence of large-scale projects worldwide and growing interest from industrial and institutional stakeholders. However, despite its huge potential for decarbonizing industrial and energy sectors green hydrogen will continue to be faced with significant challenges, particularly in the areas of the cost of production, infrastructure deployment technology maturity, as well as regulatory frameworks. The future of this sector is therefore dependent on ongoing technological advancement as well as cost reductions brought about from economies of size, increased public policy support and increased cooperation between parties. In this context, green hydrogen emerges as a strategic energy vector, expected to play a central role in the transition toward a sustainable, low-carbon, and resilient energy system.

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