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REVIEW

Green hydrogen as a source of renewable energy: a step towards sustainability, an overview

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Abstract
Hydrogen has emerged as a promising energy source for a cleaner and more sustainable future due to its clean-burning nature, versatility, and high energy content. Moreover, hydrogen is an energy carrier with the potential to replace fossil fuels as the primary source of energy in various industries. In this review article, we explore the potential of hydrogen as a part of the global energy mix and the current state of its development. The majority of hydrogen production currently occurs through steam methane reforming, which produces significant greenhouse gas emissions and limits the potential of hydrogen as a clean energy source. Significant investment and advancements in renewable hydrogen production through electrolysis are necessary to overcome this limitation. There is also a growing demand for hydrogen infrastructure, including hydrogen refueling stations and storage and transportation systems, which are crucial for the growth and success of the hydrogen industry. The future of hydrogen as a part of the global energy mix will depend on continued investment and commitment to develop and commercialize this promising energy source. Our review also explores the relationship between eco-industrial parks and hydrogen production, including the benefits and challenges of hydrogen production in EIPs and the various technologies being developed to facilitate this process.

Keywords Greenhouse gas emissions · Renewable energy · Electrolysis · Hydrogen infrastructure · Hydrogen industry

1 Introduction

Since the beginning of the nineteenth century, there is a Long-term alteration in temperature and weather patterns which is known as climate change has been happening, which may be naturally occurring as a result of variations in the solar cycle. Mankind has been responsible for these changes through their activities, especially the use of coal, oil, and gas, as fossil fuels (Germanier & Moricciani, 2023). using of such fuels caused the global warming phenomenon as a result of the production of greenhouse gases, such as carbon dioxide and methane causing raising of earth's temperature, melting ice, extreme weather events, shifts in ecosystems, ocean acidification, loss of biodiversity, impacts on agriculture and food security, and water scarcity and quality issues. (Ali et al., 2021).

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The major emitters of greenhouse gases are energy, industry, transportation, buildings, agriculture, and land use (Al-Ghussain, 2019). On the other hand, there is a lot of hydrogen types. However, in several countries, there is hydrogen which is considered a zero-carbon energy carrier for low-carbon transportation, industrial decarbonization, and heat provision (Khan et al., 2023). The hydrogen that meets specific sustainability criteria is referred to as green hydrogen, but it has no universally accepted definition (Abad & Dodds, 2020).

A range of processes and technological pathways that use both renewable and non-renewable feedstocks can be used to produce hydrogen, including natural gas, coal, nuclear, biomass, solar, and wind (Muritala et al., 2020). Renewable energy costs have dropped significantly in recent years and are anticipated to decrease even further. In many parts of the world, wind and solar power are already the least expensive forms of energy for newly built generating capacity, and their average cost is frequently lower than wholesale grid prices (Nikolaidis & Poullikkas, 2017). Our review aims to explain the nature of Traditional fuels its drawbacks. They are moreover, comparing it with green hydrogen as an alternative source of clean energy explaining the nature of green hydrogen and its process and cost of manufacturing as it is considered a future of clean Sources of Renewable Energy.

1.1 Traditional fuels

Traditional fuels have been considered the cornerstone of global energy production for ages, including fossil fuels like coal, oil, and natural gas, which play a very important role in supplying power to industries, transportation systems, and households around the world. In addition, traditional fuels also encompass wood, biomass, and peat, which have been utilized for heating and cooking purposes throughout history. As a result of using such fuels extensively and burning them, it produces a lot of waste gases that are released into the atmosphere and cause severe damage, in addition, carbon dioxide is considered the prominent combustion product, as its level in the atmosphere has started to rise since using fuel fools in industries (Schobert, 2013).

As a result of this, global warming occurs because carbon dioxide absorbs infrared radiation and traps heat, A phenomenon that has caused significant disturbance to the global climate (Soeder, 2021).

1.2 Types of traditional fuels

Traditional fuels have three main types, (coal, natural gas, and oil) all can be used to produce energy.

1.2.1 Coal

Coal is considered a solid form of fossil fuel formed by the accumulation of decaying land vegetation over millions of years, when earth layers are compacted and warmed over time, coal is formed by the deposits. Compared to the other types of fossil fuels, coal is quite abundant. Scientists predict that the global use of coal will increase as oil supplies become rare. They also estimate that the current coal amount may last for at least 200 years. In the middle of the twentieth century, people's consumption of coal doubled, and then using it decreased again in 1996, In many developing countries like India, using coal is the most popular because they can't get oil or natural gas (McKinney & Schoch, 2003; Speight, 2021).

Using coal cause air pollution, greenhouse gas emissions, contribution to climate change, environmental degradation from mining, and health hazards associated with coal mining and combustion. Over the past few years, China has documented over 10,000 instances of pneumoconiosis annually, while cases of coal workers' pneumoconiosis have emerged in developed nations like Australia and the United States. Hence, replacing it with more safe method significant importance in safeguarding the well-being of coal workers worldwide (Liu, et al., 2022).

1.2.2 Natural gas

It's the gaseous form of fossil fuels, which is versatile, and abundant, and compared to coal and oils it's considered a clean energy source. It's formed over time by the remaining marine microorganisms. Using coal was more dominant than natural gas until 1999. Many people are afraid that one day natural gas supplies will run out and some scientists say that will be soon. natural oils are the most distributed source of fossil fuels around the world as they consist of methane which can be compressed in very small volumes and penetrate the earth (Faramawy, et al., 2016). Natural gas exhibits roughly half the CO_2 emissions compared to other conventional fossil fuels which contribute to climate change (Gürsan & de Gooyert, 2021).

1.2.3 Oils

Oil is the liquid form of fossil fuel which is also formed from the remains of marine microorganisms' accumulation on the sea floor. Oils are the globally most used type of fossil fuel. it contains many different organic compounds, which can be turned into different important products in a refining process, but it is not easy to have, so many wars have been done in oil supplies. ex, Gulf War of 1991(Stephanie, 2022), which also includes high carbon emissions contributing to climate change, and air pollution (McKinney & Schoch, 2003; Passow, 2016).

The main drawbacks of oils as traditional fuels is the environmental risks associated with climate change, and health hazards from exposure to pollutants (Stephanie, 2022).

1.3 Method of preparation of traditional fuels

Fossil fuel is a mixture consisting of several layers, including the decomposing remains of plants and animals that were buried under layers of rocks and sediments for thousands of years, and later turned into carbon-rich materials. Fossil fuels go through several stages through which coal, oil, and natural gas are formed, depending on the factors of heat and pressure (Schobert, 2013), and these stages are listed in the following.

1.3.1 The beginning

When fossil fuels are exposed to the sun, they produce energy, which leads to photosynthesis, in which carbon dioxide and water of plants and animals are changed into molecular building blocks. Where carbon and hydrogen atoms contribute to building the bodies of plants and animals, so energy is stored inside carbon compounds, which, when exposed to combustion, result in energy (Berner, 2003; Zohuri & Zohuri, 2019).

1.3.2 Decomposition

When fossil materials are located much deeper under the surface of the earth, they are exposed to heat and pressure increasingly, as the high temperature leads to the fragmentation of fossil particles, as kerogen is produced in the first stage from plankton and peat from plants. They are also considered sources of energy, but they contain small amounts of energy compared to natural gas, coal, and oil (Huc, 2013).

1.3.3 Fossil fuels form

Fossil materials, after remaining in the ground for millions of years, are exposed to the process of converting the compounds from which plankton and plants are formed into fossil fuels, as plankton change into oil and natural gas, while plants change into coal. Coal is mined and wells drilled to obtain natural gas and oil, on land and sea, due to their importance in generating electricity and contributing to industries, especially the chemical industries, because they contain basic components needed for these industries, and this is because when they are burned, they produce energy (Afonja, 2020).

1.3.4 The chemical breakdown

Crude oil comprises a myriad of distinct molecules consisting predominantly of hydrogen and carbon compounds. Each deposit of crude oil possesses a distinctive composition and relative abundance of these hydrocarbons. The chemical makeup of crude oil dictates its density, varying from thick and viscous to light and fluid. Additionally, it is categorized as either sweet or sour, depending on the residual levels of sulfur, and can exhibit a color spectrum spanning from transparent golden yellow to deep black (Berner, 2003).

1.3.5 Oil in the environment

The processes above result in the presence of oil naturally in the environment under the surface of the earth at a great depth or on the sea beaches in the form of tar or bubbles (Payne, 2018).

1.4 Drawbacks of fossil fuels

- One of the main disadvantages of fossil fuels is pollution because when they are burned, carbon dioxide gas is produced, which caused the emergence of the global warming phenomenon that the world suffers from to this day. Carbon dioxide gas is produced when coal is burned compared to burning gas and oil, but sulfur dioxide is also produced when coal is burned, which is one of the gases that cause acid rain (Notz, et al., 2011).
- Many vast areas are destroyed as a result of coal mining, which harms the land as well as the environment. The process of extracting coal is very difficult, as the lives of miners are always at risk, and many workers die during the mining process, as it is one of the most dangerous jobs in the world (Stewart, 2020).
- Stations that use fossil fuels are forced to provide reserves of large quantities of fossil fuels, especially those that use coal to generate electricity, but it is always difficult to provide sufficient quantities for the station to keep safely for a long time.

- The use of some types of fossil fuels, such as natural gas and others in some places, as well as public transportation, leads to unpleasant odors for some, as well as some problems if someone suffers from an allergy.
- One of the causes that lead to exposure of the environment to risks, as well as pollution, is the use of crude oil, and it usually occurs as a result of the exposure of oil tankers to sinking under the sea level or exposure to leakage for some reason, as crude oil contains toxic chemicals that lead to air pollution when burned.

To achieve de-carbonization of the planet, most countries set the goal of using elements like hydrogen to reduce CO2 emissions.

2 What is hydrogen and how does it work?

Hydrogen is an element that exists in gaseous form and can be produced through a variety of methods. The most common method of hydrogen production is steam methane reforming, which involves the reaction of natural gas with high-temperature steam to produce hydrogen and carbon dioxide. Hydrogen can also be produced from renewable energy sources like wind, solar, and water through electrolysis (Vidas & Castro, 2021).

Once produced, hydrogen can be used in a variety of applications, including fuel for transportation, heating, and electricity generation. In transportation, hydrogen fuel cells can be used to power vehicles, which produce only water and heat as by-products. In electricity generation, hydrogen can be burned to produce electricity or used in fuel cells to generate electricity through a chemical reaction with oxygen (Ferraren-De Cagalitan & Abundo, 2021).

2.1 The potential of hydrogen in the global energy mix

Hydrogen has the potential to play a significant role in the global energy mix due to its clean-burning nature, versatility, and high energy content. In the transportation sector, hydrogen-powered vehicles have the potential to replace traditional gasoline-powered vehicles and thus, reduce greenhouse gas emissions. In addition, hydrogen can be used as a fuel for electricity generation, which can help to integrate renewable energy sources into the grid, as well as improve energy storage capabilities (De Blasio, 2021).

Furthermore, hydrogen can be stored and transported easily, making it a valuable energy source for grid stability and energy security. It can also be used as a complementary energy source to support the integration of intermittent renewable energy sources like wind and solar into the grid (Li, et al., 2020).

In the search for cleaner and more sustainable energy sources, hydrogen has emerged as a promising alternative to traditional fossil fuels. Hydrogen is the lightest and most abundant element in the universe, and when burned, its only by-product is water. This clean-burning nature, combined with its versatility and high energy content, has made hydrogen a promising energy source for the future. In this review article, we will explore the potential of hydrogen as a part of the global energy mix and the current state of its development (Sazali, 2020).

3 Types of hydrogen

The energy source and method of production used to create molecular hydrogen determine whether it is classified as grey hydrogen, blue hydrogen, or green hydrogen (Nikolaidis & Poullikkas, 2017).

3.1 Grey hydrogen

The most prevalent form of hydrogen. Steam methane reforming (SMR) or auto-thermal reforming (ATR) is used to split natural gas into hydrogen and CO_2 in a process similar to blue hydrogen. However, CO_2 is not captured and is released into the atmosphere (Nikolaidis & Poullikkas, 2017).

According to Enel's head of business development, hydrogen has been labeled a "climate killer" due to its mostly grey production process. The production of hydrogen through steam reforming and gasification is responsible for a significant amount of carbon emissions each year, equivalent to the combined emissions of Indonesia and the United Kingdom. In contrast, only a small percentage of hydrogen, approximately 2%, is generated through electrolysis (Modh, 2022). It should be noted that grey hydrogen is not considered a low-carbon fuel, as per the study conducted by Yu, et al. (2021).

3.2 Blue hydrogen

Blue hydrogen, similar to grey hydrogen, is produced through steam methane reforming or gasification. However, in the case of blue hydrogen, the carbon emissions generated during the production process are captured and stored, making it a more environmentally friendly option (Yu, et al., 2021). This carbon capture process is known as Carbon Capture Usage and Storage (CCUS) (Folger 2017). Industries that rely on fossil fuels, including heavy industries and power generation companies, have been implementing carbon capture and storage (CCS) technology to reduce their carbon footprint. While not perfect, this technology can capture up to 90% of the CO2 produced, resulting in a significant improvement (Rashid et al. 2020).

3.3 Green hydrogen

According to Proost (2020), the production of green hydrogen involves the use of electrolysis, which splits water into hydrogen and oxygen. Green hydrogen is described as having been produced by a renewable energy source, such as wind or solar power (Gondal, et al., 2018). Without causing any harm, we can use the green hydrogen and release oxygen into the environment. Although the technique of using energy to split water is expensive, it is far more environmentally benign than the process of creating grey hydrogen (Qureshi, et al., 2022). That makes green hydrogen the cleanest option (Hassan, 2023).

And there are other minor types of hydrogen such as.

3.4 Black and brown hydrogen

According to Eswaran et al. (2021), black and brown hydrogen, which are produced using black coal or lignite, are the opposite of green hydrogen and are the most environmentally harmful. These terms are sometimes used interchangeably to refer to any hydrogen produced by gasification from fossil fuels, as noted by Cho et al. (2023).

3.5 Pink hydrogen

Pink hydrogen, also known as purple or crimson hydrogen, is produced using nuclear energy to power the electrolysis process (Nadaleti et al. 2022). Furthermore, the heat generated by nuclear reactors can be used to produce steam for more efficient electrolysis or steam methane reforming that relies on fossil gas (Xu et al., 2023).

Pink hydrogen is usually considered green because it does not produce CO_2 emissions during operation (Ajanovic, et al., 2022).

3.6 Turquoise hydrogen

Turquoise hydrogen is a relatively new category of hydrogen, and there is currently no evidence of large-scale production. The production of turquoise hydrogen involves methane pyrolysis, which generates both solid carbon and hydrogen. This method has the potential to be a low-emission source of hydrogen if the heating process is powered by renewable energy and the carbon produced is either permanently stored or used (Karmaker et al. 2022).

3.7 Yellow hydrogen

Yellow hydrogen is a relatively new phrase for hydrogen made through electrolysis using solar power (Newborough & Cooley, 2020).

3.8 White hydrogen

White hydrogen is a type of naturally occurring geological hydrogen produced by fracking and found in subsurface deposits. Currently, there are no plans to utilize this hydrogen (Lemieux, et al., 2019).

4 Advantages of using green hydrogen over traditional fuels

There are several advantages of using green hydrogen over traditional fuels:

	Green hydrogen	Traditional fuels
Environmental sustainability	Green hydrogen is produced through electrolysis, using renewable energy sources such as solar or wind power. This production process releases no greenhouse gas emissions, making it a clean and sustainable fuel option. (Agaton, et al., 2022; Yu, et al., 2021)	Traditional fuels like gasoline and diesel contribute to air pollution and carbon emissions, exacerbating climate change (Agaton, et al., 2022; Yu, et al., 2021)

	Green hydrogen	Traditional fuels
Resource availability	It can be produced from renewable sources like solar, wind, and hydroelectric power ensuring a virtually limitless supply, as they are endless resources (Hassan, 2023)	Fossil fuels are finite resources and are becoming increasingly difficult and costly to extract (Hassan, 2023)
Air quality improvement	Combustion of hydrogen is more safe than traditional fuels as it produces only water vapor, improving local air quality and reducing pollution-related health risks (Hassan, 2023)	Combustion of fossil fuels is very dangerous as it releases pollutants such as sulfur dioxide, nitrogen oxides, and particulate matter, contributing to air pollution and respiratory problems which increase the risk of health problems (Perera & Nadeau, 2022)
Decentralized energy production	Green hydrogen production can be decentralized, allowing for localized energy production and reduced dependence on centralized energy infrastructure. This can enhance energy security, especially in remote areas or regions with limited access to traditional fuel sources (Hassan, 2023)	In contrast, Fossil fuel extraction and distribution are often centralized, leading to dependence on large corporations and centralized infrastructure (Hassan, 2023)
Potential for sector integration	Green hydrogen has high potential for sector integration due to its versatility and compatibility with various sectors, including transportation, industry, power generation, and heating. It can be used as a fuel for fuel cells in vehicles, as a feedstock for industrial processes like ammonia production, and as an energy storage medium for renewable energy systems (Marouani, et al., 2023)	Traditional fossil fuels are primarily used in specific sectors, such as transportation, electricity generation, and industrial applications, with limited cross-sector integration. While some efforts have been made to use fossil fuels more efficiently across sectors, such as combined heat and power (CHP) systems, their application is often constrained by environmental and regulatory factors (Marouani, et al., 2023)
Technological advancements	Advancements in electrolysis technology allow for more efficient production of hydrogen from renewable sources like solar and wind power. Innovative electrolyzers with higher efficiency and durability are being developed (Marouani, et al., 2023)	Technological advancements in fossil fuel extraction and processing have been limited, with most improvements focused on efficiency and emissions reduction in combustion processes (Abas, et al., 2015)

	Green hydrogen	Traditional fuels
Cost reduction	Falling costs of renewable energy sources such as solar and wind power contribute to lower electricity costs for green hydrogen production. Decreasing costs of electrolyzer technologies and economies of scale are driving down the cost of green hydrogen (Marouani, et al., 2023)	While extraction and processing costs for fossil fuels have remained relatively stable, concerns over environmental regulations and carbon pricing may increase operational costs in the long term (Marouani, et al., 2023)

5 Green hydrogen safety in use and storage

To determine how safe hydrogen is, it must be compared to other conventional fuels like gasoline, propane, and diesel. Green hydrogen has been demonstrated to be safer than conventional fuels in several ways, while no fuel can be guaranteed to be 100% safe (Dash, et al., 2022).

Unlike traditional fuels, hydrogen has no harmful effects. On the other hand, a lot of traditional fuels are carcinogenic or contain potent carcinogens:

– Vehicles that use hydrogen fuel cells only emit water when they are operating, whereas vehicles that burn conventional fuels produce dangerous air pollution (Ahmadi & Kjeang, 2015).
– While a hydrogen leak or spill won't harm the environment or endanger human or animal health, a leak, spill, or fire involving fossil fuels might have serious negative effects on both (Sadhu, et al., 2018).
– Hydrogen is 57 times lighter than gasoline vapor and 14 times lighter than air. In other words, when released, hydrogen usually rises and disperses quickly, hydrogen rises through the surrounding air at a rate of 20 m per second, enabling quick fuel dispersion in the event of a leak and preventing it from staying close to the ground where people are in the event of a fire. However because the vapor from gasoline and propane is heavier than air, it is more likely to remain at ground level, increasing the chance of fires that could endanger people and structures (Aziz, 2021).
– As hydrogen is known to have a lower radiant heat than conventional gasoline, thus the air around its flame is always less hot than that of normal gasoline. Consequently, there is less chance for secondary flames of hydrogen (Aziz, 2021).
– More oxygen is required for hydrogen to explode thus it is safer than fossil fuels, hydrogen requires more oxygen to explode. Oxygen concentrations of between 18 and 59 percent can make hydrogen explosive, whereas oxygen concentrations of between 1 and 3 percent can make gasoline explosive. This indicates that in any given atmosphere with oxygen, gasoline presents a greater risk of explosion than hydrogen (Khandelwal, et al., 2013).
– Hydrogen is the most diffuse fuel currently on the market. If hydrogen is accidentally started, the fire will not only extinguish far more quickly than an oil or gas fire, but it will also burn up and away. One of hydrogen's inherent safety features is that it does not linger outside of a container (Najjar, 2013).

Hydrogen safety remains a top focus for research and development. At the federal level, the Department of Energy funds research and development (R&D) projects related to hydrogen safety through its office for hydrogen and fuel cell technologies, helping to ensure that hydrogen can continue to be a secure fuel that can assist in decarbonizing our future energy requirements (Miller, et al., 2020).

Today, the National Fire Protection Association, International Code Council, and Hydrogen Industry Panel on Codes collaborate to provide strict standards for hydrogen systems and fuel cells. It has been feasible to provide the right engineering controls and recommendations to reduce the risks associated with hydrogen's high flammability and low ignition energy thanks to years of research and development and expertise (Foorginezhad, et al., 2021).

Sensors are necessary for hydrogen fueling stations, equipment, and facilities because hydrogen has no color and no odor. With the use of modern technology, hydrogen leaks can be robustly detected using remote hydrogen sensing. Before deployment, hydrogen storage tanks in fuel cell vehicles must pass stringent testing requirements, including being exposed to high temperatures and pressures. These are just a few instances of the norms and regulations that have helped the hydrogen sector function safely over the past forty years (Wang, et al., 2020).

6 Green hydrogen production cost

Several factors, including economic and technical aspects, can impact the cost of producing hydrogen from natural gas, with gas prices and capital expenditures being the two most crucial factors (Maggio, et al., 2019).

The main cost element is fuel, 45% to 75% of production expenses are attributable to this. Because of low gas prices in North America, the Middle East, and Russia, some of the lowest hydrogen production costs exist. Higher gas import prices force gas importers such as Japan, Korea, China, and India to increase hydrogen production costs (Lebrouhi et al., 2022).

Although water electrolysis currently represents less than 0.1% of global hydrogen production, its potential is growing due to declining costs for renewable electricity, particularly from solar PV and wind sources. There is increasing interest in electrolytic hydrogen as a low-carbon fuel.

Building electrolyzers in locations with abundant renewable energy resources has the potential to become a cheaper method for hydrogen production, even after adding the cost of the transportation of hydrogen from the production sites to end-users (Ayodele & Munda, 2019).

The production of green hydrogen costs about 2 dollars per kg (based on current US prices) (Xiang, et al., 2021). Brown hydrogen costs 2 dollars per kg and is created from cheap coal (Longden, et al., 2022).

Costs for blue hydrogen, which is produced from natural gas and carbon capture and storage, range from $5 to $7 per kg in the US to $7 to 11 per kg in Europe and Australia (Khan, et al., 2021). The cost of green hydrogen production from renewable energy using electrolysis using ranges from US$10 to US$15 per kg (Phoumin, 2021).

Grey hydrogen created with inexpensive natural gas from fracking costs US$2 per kg in the US, but due to increased natural gas prices in Europe, Australia, and Asia, it costs

	Hydrogen Types	Carbon Intensity	Production $/kg H2
Green Hydrogen	SGH2 Greener than green hydrogen	Depending on feedstock, it can be up to -200gCO2eq/MJ (less than 0 kg of CO2 per kg of H2)	$2 - $3
Green Hydrogen	Green Hydrogen (Electrolysis)	0gCO2eq/MJ	$6 - $8
Hydrogen From Fossil Fuels	Grey Hydrogen from NatGas	+12 kgCO2/kgH2	$2 - $6 (cost natural gas)
Hydrogen From Fossil Fuels	Brown Hydrogen from Gasification of coal	+20 kgCO2/kgH2	$2 - $3
Blue Hydrogen With Carbon Capture & Sequestration	Grey Hydrogen	+12 kgCO2/kgH2 with ccs	$4 - $8
Blue Hydrogen With Carbon Capture & Sequestration	Brown Hydrogen	+20 kgCO2/kgH2 with ccs	$4 - $5

Fig. 1 Summary of hydrogen production costs

US$5–6 per kg (Chang13 & Phoumin14, 2021). A summary of the costs of hydrogen production is presented in Fig. 1.

According to Connelly et al. (2020), the demand for hydrogen was approximately 87 million metric tons (MT) in 2020, and it is expected to rise to 500–680 million MT by 2050. The hydrogen market was worth $130 billion in 2020 and is projected to increase by up to 9.2% annually until 2030. However, the majority of hydrogen produced today is generated from fossil fuels, with only a small fraction of it being "green." Currently, 6% of the world's natural gas and 2% of its coal are utilized to produce hydrogen (Megia et al., 2021).

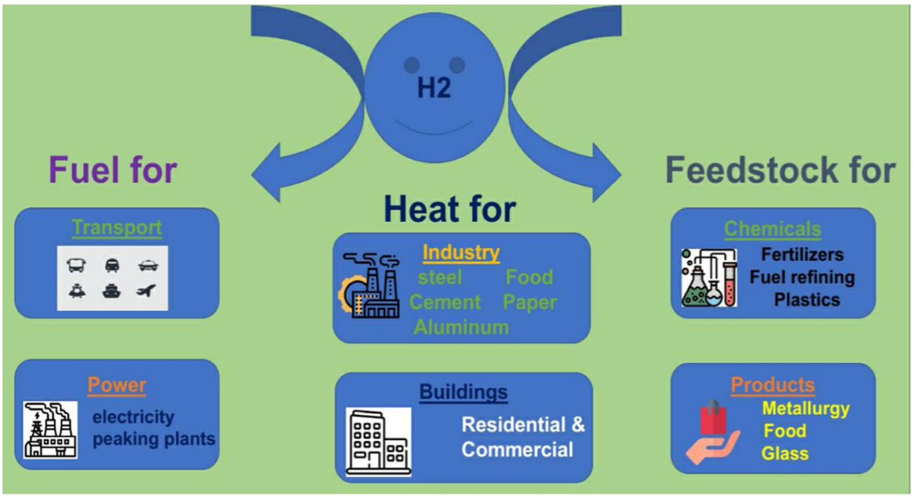

Fig. 2 The main uses of green hydrogen

Despite this, green hydrogen production technologies are gaining momentum due to hydrogen's expanding range of applications in several industries, including power generation, steel and cement manufacturing processes, fuel cells for electric vehicles, heavy transportation like shipping, production of green ammonia for fertilizers, cleaning products, refrigeration, and grid stabilization (Medvedenko & Voitas, 2022). A summary of green hydrogen uses is presented in Fig. 2.

Moreover, the commercial viability of green hydrogen production has increased due to the declining cost of renewable energy sources, decreasing electrolyzer costs, and increased efficiency brought on by technological advancements. The forecast of the levelized cost of hydrogen generation for major projects worldwide through 2050 is depicted in the picture below (Medvedenko & Voitas, 2022).

According to Bloomberg New Energy Finance 2020, the estimated cost of producing green hydrogen may range from \$0.70 to \$1.60 per kg in most parts of the world by 2050, as shown in Fig. 3. This cost projection suggests that green hydrogen may become cost-competitive with natural gas if these costs continue to decrease. NEL, which is the largest producer and manufacturer of electrolyzers worldwide, predicts that the cost parity or even superiority of green hydrogen production over fossil fuels could be reached as early as 2025 (Lebrouhi et al., 2022).

7 Can green hydrogen become the oil of a new era?

A new arrangement of energy trade relations might be ushered in by hydrogen and its derivatives. Some regions most notably those in Europe and northeast Asia are preparing to increase their hydrogen imports, while others like Australia aspire to become big exporters or possibly world leaders in renewable energy (Dunn, 2002).

Australia and countries in the Middle East and North Africa, for example, have several advantages: they can leverage their existing energy trade relations, skilled workforce, and

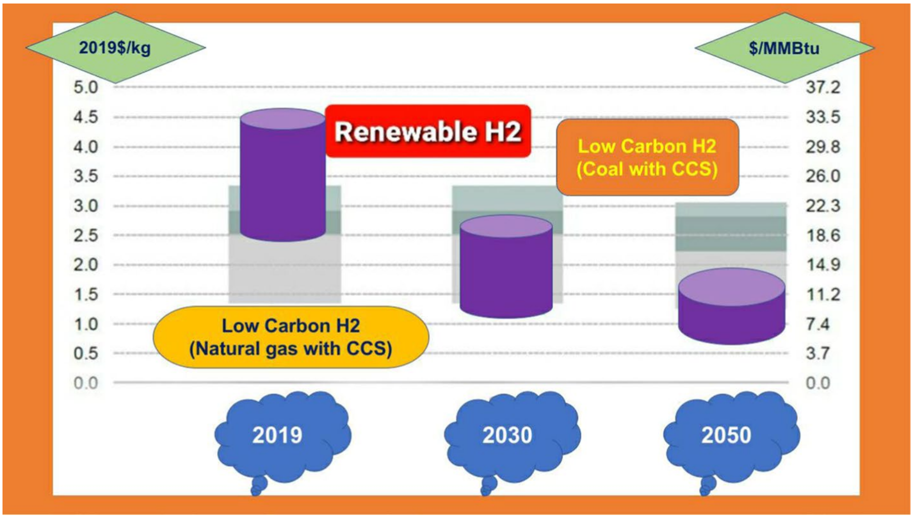

Fig. 3 The estimated decrease in green hydrogen production cost

established infrastructure to become clean hydrogen exporters. It is an appealing way for them to diversify their economies while remaining energy exporters (Dunn, 2002).

Ghosh and Chhabra (2021) reported that the Green Hydrogen Catapult, a United Nations initiative, has nearly doubled its target for green electrolyzers from 25 to 45 gigawatts by 2027, in a bid to reduce the cost of green hydrogen. The European Commission has also taken action to promote renewable and low-carbon gases, including hydrogen, and ensure energy security for all Europeans through a set of legislative proposals aimed at decarbonizing the EU gas market (Ghosh and Chhabra 2021). Moreover, Japan has announced its plan to invest $3.4 billion from its green innovation fund to accelerate research and development and promote the use of hydrogen over the next decade, to hold one-fourth of the global low-carbon hydrogen market by 2030 (Taibi et al. 2020).

According to a McKinsey study, the hydrogen economy in the United States could generate 140 billion dollars and support 700,000 jobs by 2030 (Renee, 2021).

The following advantages of green hydrogen contribute to making it the oil of the new era and the highest share of the investments of the countries of the world:

Safety of Green Hydrogen?

(This part has been mentioned in detail before in Green Hydrogen Safety in Use and Storage).

According to the Office of Energy Efficiency & Renewable Energy, hydrogen is considered safer than current fuels due to several characteristics, such as its non-toxic nature and its ability to quickly evaporate and disperse in the event of a leak due to its lighter-than-air properties (Office of Energy Efficiency & Renewable Energy)(Tashie-Lewis & Nnabuife, 2021).

8 Various uses for hydrogen

Hydrogen is now widely used in industry and the production of many chemicals such as methanol, ammonia, and steel, and consequently this results in reduced emissions (Griffiths, et al., 2021).

The competitiveness of hydrogen fuel cell cars is dependent on fuel cell costs and refueling stations, as the priority for trucks is to reduce the delivered price of hydrogen. Shipping and aviation have few low-carbon fuel options, creating an opportunity for hydrogen-based fuels (IEA, 2019).

The direct use of hydrogen in hydrogen boilers or fuel cells is included also in long-term prospects. Hydrogen can be mixed with the already-used natural gas networks in various buildings in the big cities, showing the greatest potential (Maestre, et al., 2021).

In the power generation industry, hydrogen can be used for storing renewable energy. Moreover, in gas turbines hydrogen can be used with ammonia to increase the flexibility of the power system. Also, ammonia can be used in coal-fired power plants to cut emissions (Lee & Lee, 2021).

The time has come to capitalize on hydrogen's potential to play a key role in a clean, secure, and affordable energy future:

The International Energy Agency (IEA) has created this historic report at the request of the government of Japan, which is currently holding the G20 presidency. It analyses the current situation regarding hydrogen and provides recommendations for its future development. According to the report, clean hydrogen is currently experiencing unheard-of political and commercial momentum, with a rapid increase in global policies and projects. It concludes that to make hydrogen more widely used, it is crucial to scale up technologies and reduce costs. It will be possible to fully capitalize on this growing momentum thanks to the practical and doable recommendations made to governments and businesses (IEA, 2019).

According to IEA (2019), hydrogen can play a critical role in overcoming energy challenges and provide a solution to decarbonize various industries like long-distance transportation, chemicals, and iron and steel. Moreover, it can enhance energy security and improve air quality. In addition, renewable energy sources could benefit significantly from hydrogen, as it can help store energy from sources such as wind and solar PV. Hydrogen has the potential to be the most cost-effective way to store electricity for extended periods. It also offers the possibility to transport energy over long distances from areas with abundant renewable resources to energy-deficient cities. IEA (2019) further notes that while hydrogen has had false starts in the past, recent successes in solar PV, wind, batteries, and electric vehicles show that policy and technological innovation can establish global clean energy industries.

As the global energy sector transforms, the versatility of hydrogen is attracting interest from a broader range of governments and businesses. Key stakeholders, such as energy importers and exporters, renewable energy providers, industrial gas producers, power and gas utilities, automobile manufacturers, oil and gas companies, major engineering firms, and cities, are lending their support. The investment in hydrogen can drive technological and industrial development in economies worldwide, resulting in the creation of skilled jobs (IEA, 2019).

8.1 The IEA's top 7 recommendations for scaling up hydrogen (IEA, 2019)

1. Governments and companies should include hydrogen in their long-term energy strategies, particularly in sectors such as refining, chemicals, iron and steel, freight and long-distance transportation, buildings, and power generation and storage.
2. To increase demand for clean hydrogen, policies that support sustainable markets for clean hydrogen and limit emissions from hydrogen derived from fossil fuels are necessary. This will require investments from suppliers, distributors, and users.
3. To address investment risks for first-movers in hydrogen deployment, governments can provide loans, guarantees, and other mechanisms with specific objectives and time restrictions.
4. Research and development are crucial to reducing costs and enhancing the performance of fuel cells, hydrogen-based fuels, and electrolyzers, as well as achieving economies of scale in production.
5. Harmonizing standards and removing regulatory obstacles, such as unclear permit requirements, inconsistent regulations across industries and nations, and safety certification, is necessary for the smooth development of hydrogen supply chains.
6. Improved international cooperation is necessary for standards sharing, cross-border infrastructure, and monitoring and reporting of progress towards long-term goals in hydrogen production and use.
7. Four crucial opportunities to build momentum for hydrogen deployment over the next ten years include utilizing industrial ports as hubs for lower-cost and lower-carbon hydrogen, utilizing existing gas infrastructure for clean hydrogen sources, supporting fuel-cell vehicles in transport fleets and corridors, and establishing the first shipping routes for international hydrogen trade (IEA, 2019).

9 Current state of hydrogen development

Despite its potential, the current state of hydrogen development is still in its early stages. The majority of hydrogen production currently occurs through steam methane reforming, which is a carbon-intensive process that produces significant greenhouse gas emissions. This limits the potential of hydrogen as a clean energy source, as it undermines efforts to reduce greenhouse gas emissions (Kakoulaki, et al., 2021).

To overcome this limitation, significant investments and advancements in renewable hydrogen production through electrolysis are needed. This will require the development of new technologies and infrastructure, as well as the commercialization of these technologies at a large scale (Dange, et al., 2021).

Additionally, there is a growing demand for hydrogen infrastructure, including hydrogen refueling stations for the development hydrogen-powered vehicles and hydrogen storage and transportation systems. These infrastructure systems are crucial for the growth and success of the hydrogen industry, as they will allow for the widespread adoption and use of hydrogen as a clean energy source (Apostolou & Xydis, 2019).

10 Relation between eco-industrial park and hydrogen production

Eco-industrial parks (EIPs) are becoming increasingly popular as a way to promote sustainable development, conserve natural resources, and reduce greenhouse gas emissions. The concept of EIPs has been gaining popularity as a way to create a more sustainable and efficient industrial ecosystem. The core idea behind EIPs is to create a cluster of industrial and commercial activities that are designed to minimize waste and optimize resource use (Boix, et al., 2015).

One of the ways that EIPs are promoting sustainable development is through the production of hydrogen. Hydrogen is an energy carrier that has the potential to replace fossil fuels as the primary source of energy in many industries. The production of hydrogen is a crucial step in the transition to a low-carbon energy system, as it can be used to produce electricity, heat, and transport fuel (Kuznetsova, et al., 2016).

In this section, we will examine the relationship between eco-industrial parks and hydrogen production. We will explore the benefits and challenges of hydrogen production in eco-industrial parks and discuss the various technologies that are being developed to facilitate this process.

10.1 Benefits of hydrogen production in eco-industrial parks

There are several benefits to producing hydrogen in eco-industrial parks.

Firstly, EIPs can provide the necessary infrastructure for the production and distribution of hydrogen. EIPs are designed to be highly interconnected, with a focus on minimizing waste and optimizing resource use. This makes them an ideal location for the production of hydrogen, as the infrastructure is already in place to support this activity (Lawal, et al., 2021).

Secondly, EIPs can reduce the costs of hydrogen production. By clustering industries together in one location, EIPs can reduce the costs of transportation and distribution, making hydrogen more affordable for businesses and consumers. Additionally, the integration of hydrogen production into EIPs can lead to greater economies of scale, further reducing the costs of hydrogen production (Lawal, et al., 2021).

Thirdly, hydrogen production in EIPs can improve energy security and reduce greenhouse gas emissions. By producing hydrogen locally, EIPs can reduce dependence on imported energy sources and reduce the emissions associated with the transportation of hydrogen over long distances. This can help to reduce the carbon footprint of the energy sector, making it more sustainable in the long term (Lawal, et al., 2021).

10.2 Challenges of hydrogen production in eco-industrial parks

While there are several benefits to producing hydrogen in eco-industrial parks, there are also some challenges that must be addressed. One of the biggest challenges is the high cost of hydrogen production. Hydrogen production is still relatively expensive, and many companies are reluctant to invest in this technology until it becomes more cost-effective (Eljack & Kazi, 2021).

Another challenge is the lack of hydrogen infrastructure. For hydrogen production to be successful in eco-industrial parks, there must be a well-developed infrastructure in place to support this activity. This includes pipelines, storage facilities, and distribution networks. Developing this infrastructure is a complex and costly process, and it may take several years to become fully established (Boix, et al., 2015).

Finally, there is a need for more research and development in the field of hydrogen production. While there has been a great deal of progress in this area in recent years, there is still much to be done in terms of improving the efficiency and cost-effectiveness of hydrogen production.

10.3 Technologies for hydrogen production in eco-industrial parks

Several technologies are being developed to facilitate hydrogen production in eco-industrial parks. One of the most promising technologies is water electrolysis. This process uses electricity to split water into hydrogen and oxygen, producing hydrogen in a clean and renewable manner (Kazi, et al., 2021).

Another promising technology is steam methane reforming, which uses natural gas to produce hydrogen. This process is well established, and many industrial plants already have the infrastructure in place to support this activity. However, this technology is not considered as environmentally friendly as water electrolysis, as it produces greenhouse gas emissions (Zhang, et al., 2022).

Biohydrogen production is also being developed as a means of producing hydrogen in eco-industrial parks. This process uses biological methods, such as fermentation or dark fermentation, to produce hydrogen from organic matter. This technology has the potential to be highly sustainable, as it uses waste materials as a feedstock, reducing the amount of waste that is sent to landfills (Wainaina, et al., 2020).

10.4 Current state of hydrogen development

Despite its potential, the current state of hydrogen development is still in its early stages. The majority of hydrogen production currently occurs through steam methane reforming, which is a carbon-intensive process that produces significant greenhouse gas emissions. This limits the potential of hydrogen as a clean energy source, as it undermines efforts to reduce greenhouse gas emissions (Kakoulaki, et al., 2021).

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In conclusion, the relationship between eco-industrial parks and hydrogen production is an important one, as it has the potential to support the transition to a more sustainable and low-carbon energy system. While there are challenges that must be addressed, such as the high cost of hydrogen production and the lack of infrastructure, there are also several benefits to producing hydrogen in eco-industrial parks. By clustering industries together, reducing costs, and improving energy security, EIPs can play a critical role in the development of a more sustainable energy system. The development of technologies such as water electrolysis, steam methane reforming, and biohydrogen production are also contributing to the growth of hydrogen production in eco-industrial parks.

11 Conclusion

Hydrogen has the potential to play a significant role in the global energy mix and the transition toward a low-carbon economy. Its clean-burning nature, versatility, and high energy content make it a promising energy source for the future. However, the current state of hydrogen development is still in its early stages, and significant investment and advancements in hydrogen production, infrastructure, and technology are necessary for it to reach its full potential. As a large amount of hydrogen is required for producing a small amount of energy, the future of hydrogen as a part of the global energy mix will depend on the continued investment and commitment of governments, industry, and researchers to develop and commercialize this promising energy source. Finally, the authors think that hydrogen will be the solution to the vast need for clean energy, so there should be a global awareness of its importance, especially in the industry field that can support its production.

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