The Hydrogen Economy and Carbon Capture Nexus: A Global Review of Pathways, Technologies, and Challenges

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Abstract: The worldwide transition to a low-carbon energy framework has established hydrogen as an essential decarbonisation mechanism, especially for challenging industrial sectors to decarbonise. The environmental advantages of hydrogen depend on its manufacturing method. Conventional "grey" hydrogen generation, mostly reliant on fossil-based technologies, is a major contributor to CO_2 emissions. This analysis examines the relationship between the hydrogen economy and carbon capture, utilisation, and storage (CCUS) technologies, facilitating the generation of "blue" hydrogen as a lower-carbon transitional fuel. The research methodically examines contemporary hydrogen generation methods, emphasising the integration of carbon capture, utilisation, and storage (CCUS) with steam methane reforming (SMR) and autothermal reforming (ATR). It offers a comprehensive analysis of post-combustion, pre-combustion, and oxyfuel carbon capture systems, assessing their maturity, efficiency, and retrofit capability. The research delineates critical obstacles confronting both "green" (electrolysis-based) and "blue" hydrogen, including elevated prices, technical underdevelopment, energy inefficiencies, and public acceptability concerns. The review asserts that although green hydrogen embodies the ultimate sustainable objective, blue hydrogen, supported by CCUS, serves a crucial transitional function in decarbonising the current hydrogen supply and industrial framework, bridging the divide until renewable hydrogen achieves economic and technological feasibility at scale.

Keywords: *Decarbonization; Sustainability; Hydrogen Economy; Carbon Capture; Energy Transition.*

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I. INTRODUCTION

The transition towards a low-carbon economy has necessitated a significant shift in global energy systems, particularly in the domains of refining and petrochemical processing. Hydrogen (H_2), long recognized for its versatility and clean-burning properties, is emerging as a cornerstone in decarbonization strategies. When combusted, hydrogen yields only water, making it a potentially ideal replacement for fossil fuels in many industrial processes and as a feedstock in chemical production. However, the source and method of hydrogen production greatly influence its overall environmental impact [1].

Currently, approximately 95% of the world's hydrogen is produced from fossil fuels, primarily through steam methane reforming (SMR) and autothermal reforming (ATR) of natural gas [2]. These methods, although mature and widely adopted, emit significant quantities of carbon dioxide (CO_2), contributing to global greenhouse gas (GHG) emissions. The conventional SMR process, for instance, emits nearly 9–12 kg of CO_2 per kg of H_2 produced [3]. This underscores the paradox of hydrogen's clean usage versus its carbon-intensive production. To reconcile this contradiction, the integration of carbon capture and storage (CCS) technologies into hydrogen production processes has gained considerable attention. This integrated model enables the capture of a substantial portion of the CO_2 generated during reforming, thereby transforming traditional "grey hydrogen" into "blue hydrogen" a lower-carbon alternative that serves as a transition fuel while green hydrogen technologies mature [4]. This review provides a comprehensive analysis of the technological pathways, global status, and socio-economic challenges facing the production of low-carbon hydrogen, with a particular emphasis on the role of fossil-fuel-based production with CCS.

II. METHODOLOGY

This review is based on a systematic analysis of recent scientific literature, industry reports, and policy documents

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from international energy agencies. The literature search was conducted using academic databases (e.g., Scopus, Web of Science) and key terms including "blue hydrogen", "carbon capture and storage", "steam methane reforming", "autothermal reforming", and "hydrogen economy". The collected information was synthesized to provide a state-of-the-art overview of the technologies, economics, and deployment status of hydrogen production with CCS, comparing it with emerging green hydrogen pathways.

III. RESULTS AND DISCUSSION

A. Hydrogen Production Pathways

Hydrogen production refers to the set of chemical and electrochemical processes that convert feedstocks (fossil fuels, biomass, water, or other carriers) into molecular hydrogen (H_2). Scholars describe the field as a spectrum of pathways distinguished by feedstock and energy source: steam methane reforming (SMR), autothermal reforming (ATR), partial oxidation and catalytic reforming of hydrocarbons, thermochemical and photocatalytic routes, chemical-looping processes, and water electrolysis (alkaline, PEM, AEM, and SOEC) [5]. Reviews emphasize that each route involves distinct reaction chemistry, thermal management requirements, and downstream purification needs; SMR and ATR are grouped as thermochemical methane-based routes that rely on high-temperature catalysis, while electrolysis routes are electricity-driven and thus coupled tightly to grid or renewable power characteristics [5].

Within fossil-fuel-based production, SMR remains the most widely applied industrial route: methane reacts with steam over Ni-based catalysts to produce syngas and, via water–gas shift, hydrogen and CO_2. Technical literature documents factors controlling SMR performance reaction kinetics, catalyst composition, steam-to-carbon ratio (S/C), reactor temperature and pressure, and heat management—reporting trade-offs between conversion, carbon formation risk, and thermal duty. Likewise, ATR is characterized in the literature as a partial-oxidation–plus-reforming route that internally couples exothermic and endothermic steps (adding O_2 to CH_4 and steam), producing syngas with different H_2/CO ratios and often exhibiting strong non-isothermal reactor behavior; authors highlight ATR's capacity for intrinsic heat balance but note sensitivity to O/C and operating profiles [6]. Electrolysis-based hydrogen production is the common descriptor for “green hydrogen” in the literature: scholars detail alkaline electrolysis, proton-exchange membrane (PEM) electrolysis, anion-exchange membrane (AEM) approaches, and high-temperature solid oxide electrolysis (SOEC). Reviews synthesize advances in electrode materials, durability, stack scale-up, and coupling with variable renewable electricity; authors report that capital costs, stack lifetime, and grid-integration strategies are central determinants of future deployment and cost trajectories [7].

The literature situates carbon management; capture, utilization, and storage (CCUS) as the defining differentiator between “gray” hydrogen (SMR without capture), “blue” hydrogen (SMR/ATR with CCS), and low-emissions hydrogen overall [6]. Empirical and modeling studies quantify capture rates, energy penalties, and lifecycle CO_2 intensities for SMR and ATR with post-combustion, pre-combustion, or solvent-based capture, reporting substantial reductions in stack emissions but also noting additional heat and electricity demands for solvent regeneration and CO_2 compression. Authors commonly express carbon intensity in $kgCO_2/kgH_2$ and compare configurations, showing that adding CCS lowers direct emissions but increases levelized cost of hydrogen depending on capture fraction and upstream methane emissions [8]. Hydrogen yield and thermal efficiency are recurring analytic themes: quantitative studies use stoichiometric limits (e.g., the SMR theoretical yield of 4 mol H_2 per mol CH_4) as baselines and then report experimental or simulated yields and thermal efficiencies under realistic operating constraints (temperature, pressure, S/C and O/C ratios, catalyst activity). Scholars model mass and energy balances in process simulators (Aspen Plus / HYSYS) to close material/energy loops and to identify major heat loads and integration opportunities (e.g., heat recovery from reformer flue gas, steam generation) [6]. Recent work also proposes refined efficiency metrics that separate hydrogen produced directly from methane reforming vs. steam contributions to better attribute energy sources in integrated systems [9].

Finally, techno-economic and system-level literature ties the concept of hydrogen production to market, policy, and infrastructure realities. Reports from energy agencies and recent TEAs synthesize LCOH/LCOE ranges for different pathways, project sensitivity to feedstock and electricity prices, and document that cost declines especially for electrolysis depend on scale, supply chains (e.g., electrolyser manufacturing), and policy supports [9]. Global trend analyses also note that announced capacity and project pipelines have evolved rapidly, prompting reassessments of realistic deployment timelines [7]. Across the reviewed scholarship, hydrogen production is consistently presented as a portfolio of technical pathways each with distinct reaction chemistry, energy flows, and system interactions; areas that empirical and modeling studies continue to map quantitatively for engineering and policy decision-making.

B. Carbon Capture Technologies

When referring to a manufacturing or industrial process, the term "carbon capture" (CC) is used to refer to a collection of technologies that successfully capture carbon dioxide (CO2) at various stages of the process. It is possible that this takes place during the combustion process or during the generation of power through other methods. The research conducted by Boot-Handford et al. [10] indicates that a number of industries, such as the production of iron and steel as well as cement, are already capable of utilising this technology as an additional step in order to collect the remaining emission, particularly from a process that is already energy-efficient.

➢ *Post Combustion Carbon Capture*

As the name suggests, post combustion technology is an additional process that is added to an existing industrial plant or power production facility. This is done in order to complete the process. The exhaust fumes that are produced as a result of the combustion of fossil fuels are typically managed by this

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additional procedure, which is typically the final stage in the process. This method is designed to separate gases into their fundamental components, which include nitrogen, water, carbon dioxide, and other minor byproducts such as sulphur and nitrous oxides. The goal of this process is to separate gases into their primary components. As a result of the fact that these technologies constitute the final link in the chain, it is inherently simpler to retrofit them to facilities that are already in operation without creating major changes to the fundamental operations that are carried out at the plant. Consequently, as a consequence of this convenience, there has been a significant rise in the level of interest in research that enables the creation of such technologies that are more developed and economically possible [11].

- *Pre-Combustion Carbon Capture*

Pre-combustion is a process that includes causing traditional fossil fuels such as coal or natural gas to react with air or oxygen, with or without the presence of steam or heat. Syngas is created when these fossil fuels are treated to the process of pre-combustion [12]. Synthesis Gas, often known as syngas, is produced as a waste product of this process. Syngas is a mixture of carbon monoxide (CO) and hydrogen gas (H2), which is also known as fuel gas, as stated by Osman et al. [13]. Syngas is a mixture of these two gases. After that, the syngas is transported to a facility dedicated to the transformation of hydrogen and carbon dioxide. While the carbon dioxide is transferred to heat recovery and steam generating units in order to generate power, the hydrogen can then be used to generate electricity or sold independently as a source of energy [14]. In addition, the hydrogen can be used to manufacture steam. In order to facilitate transportation and storage, it may be compressed once more and then dehydrated after that [15]. Given that this method has a lower energy cost in comparison to post-combustion capture, there is cause to have optimism for this methodology.

- *Oxyfuel Combustion*

Oxyfuel combustion, also referred to in the literature as oxy-firing or oxy-combustion, represents the most recent and technologically advanced of the three principal methods for carbon capture (post-combustion, pre-combustion, and oxyfuel). The fundamental principle of this technique is relatively straightforward: rather than burning fossil fuels in atmospheric air, which contains approximately 79% nitrogen and only 21% oxygen, the fuel is combusted in an environment enriched almost entirely with oxygen [11]. The replacement of nitrogen with oxygen leads to a flue gas composition that is dominated by carbon dioxide and water vapor, with nitrogen and other trace gases reduced to negligible levels. The presence of a much higher fraction of water vapor in the resulting flue gas stream allows for simpler CO_2 separation through condensation, thereby making the purification and subsequent compression of CO_2 for transport and storage considerably more straightforward than in conventional air-firing systems [16].

Despite this theoretical advantage, the practical deployment of oxyfuel combustion is accompanied by significant challenges. One of the primary operational requirements is the provision of very high-purity oxygen, which in itself is an energy-intensive and costly process. To achieve the necessary extraction and combustion rates, oxyfuel systems require either substantial heat input or operation under elevated pressures, which further raises energy demand [17]. Consequently, although the method is effective in terms of achieving high CO_2 concentrations in the flue gas, the overall energy penalty can offset its advantages, reducing the net efficiency of the power plant or industrial facility in which it is applied. Florin and Fennell [18] argue that the efficiency of CO_2 extraction is significantly undermined by the large heat duty required in oxygen-fired boilers and the potential for atmospheric air infiltration into the combustion chamber, both of which dilute CO_2 purity and increase costs. Scholars and industry experts have therefore investigated the potential of carbon capture technologies such as oxyfuel combustion across various industrial sectors to determine their role in mitigating anthropogenic climate change. A number of critical analyses and pilot studies have been conducted to assess how carbon capture could be integrated into existing power systems and large-scale industrial plants. These studies not only examine the capture efficiency but also evaluate the interface between capture systems and national electricity grids, addressing concerns such as system stability, dispatchability, and the balance of power and emissions [19].

At present, however, the widespread commercial deployment of carbon capture remains limited. According to the U.S. Department of Energy's National Energy Technology Laboratory [20], there are approximately 90 carbon capture projects under continuous development worldwide. While this figure is encouraging, it remains far below the scale required to meet global emission-reduction targets for 2050. The slow pace of adoption is due largely to a combination of economic, technological, and commercial barriers, including high upfront capital costs, the absence of supportive policy frameworks in some regions, and uncertainty about long-term CO_2 storage liability [21].

Nonetheless, one of the most compelling strengths of carbon capture particularly oxyfuel systems is their ability to be retrofitted onto existing energy infrastructure with relatively modest adjustments. Unlike renewable energy systems, which often require new grid connections, large land areas, and intermittency solutions, carbon capture can be integrated into current fossil-fuel plants to deliver immediate emissions reductions without disrupting energy supply. Several techno-economic comparisons suggest that CCS is often more cost-effective in the short to medium term compared to large-scale renewable energy deployment and, critically, can be implemented within shorter timeframes [22]. In addition, carbon capture, including oxyfuel, is especially well suited to energy-intensive industries such as cement, steel, and power generation, where process emissions cannot easily be mitigated by renewable electricity alone. For such sectors, CCS offers a pathway to decarbonization while maintaining production capacity. The technology's appeal is further enhanced by its dual function: while reducing CO_2 emissions, it still enables the continued use of fossil fuels to produce reliable energy or process heat, which remains important in regions where renewable penetration is low [19].

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Nevertheless, it is important to emphasize that carbon capture and storage should not be viewed as a substitute for other climate action measures such as improving energy efficiency or scaling up renewable energy capacity. Rather, it should be positioned as a complementary solution one that buys time by reducing emissions from existing infrastructure while longer-term transitions to sustainable energy systems are underway [23]. The slow progress in global deployment highlights the persistent obstacles facing oxyfuel and related CCS technologies. Chief among these are the economic costs of oxygen production and CO_2 compression, the technological risks associated with large-scale boiler modifications, and the commercial uncertainties tied to carbon markets and regulatory frameworks. Yet, despite these barriers, continuous research and development have yielded promising improvements in capture efficiency, solvent design, and oxygen separation methods. Current pilot projects are steadily narrowing the performance gap, with projections suggesting that by 2050, CCS technologies including oxyfuel combustion could play a central role in achieving global emission reduction goals [23].

C. Equations

As the world moves closer to achieving Net Zero, there has been a discernible increase in the number of carbon capture and storage installations. In accordance with the information that was made public by the Global CCS Institute, there are thirty commercial plants that are now in operating all around the world [24]. The natural gas processing business is placed first, with the biggest number of facilities, followed by the fertiliser industry, then the ethanol and hydrogen production industries (Table 1). These operational facilities, which include both commercial and pilot facilities, are used in a variety of different industries.

North America is in the lead with 16 commercial facilities that are now operating, according to the distribution of carbon capture and storage facilities throughout the world [24]. The areas that follow North America are Asia Pacific, Europe, the Middle East, Africa, and South Africa (Figure 1). The United States of America has the biggest number of carbon capture and storage (CCS) facilities on a global scale, with twelve facilities. This is followed by Canada, China, Norway, Brazil, Algeria, the United Arab Emirates, the Kingdom of Saudi Arabia, Qatar, Australia, Norway, Hungary, and Iceland (Figure 2).

According to the yearly worldwide state of carbon capture and storage report series that was published by the worldwide CCS Institute, the number of carbon capture and storage facilities has shown a discernible growth from 2015 to the present day (Figure 3). There is a consistent pattern seen with regard to the capturing capability of the target gas (Figure 4).

Table 1 Number of CCS Facilities in Different Industries

Facility Industry	**Number of CCS Facilities**
Natural gas processing	14
Fertilizer production	4
Ethanol production	3
Hydrogen production	2
Direct air capture	1
Power generation	1
Oil refining	1
Chemical production	1
Synthetic natural gas	1
Methanol production	1
Iron and steel production	1
TOTAL	30

Source: [25]

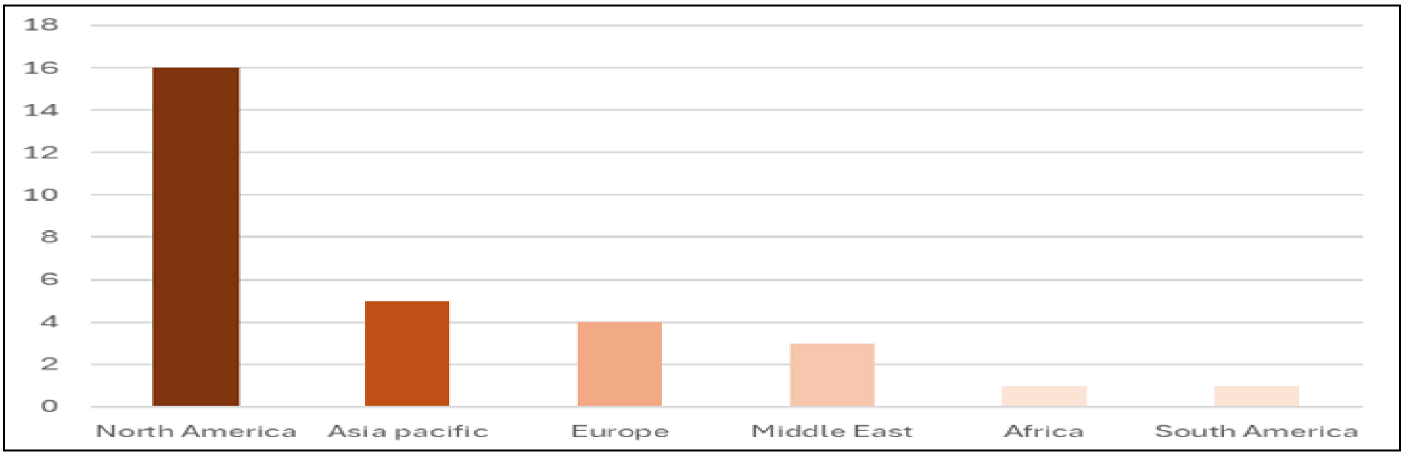

Fig 1 Number of Operational Commercial CCS Facilities in Different Regions
(Source: [25])

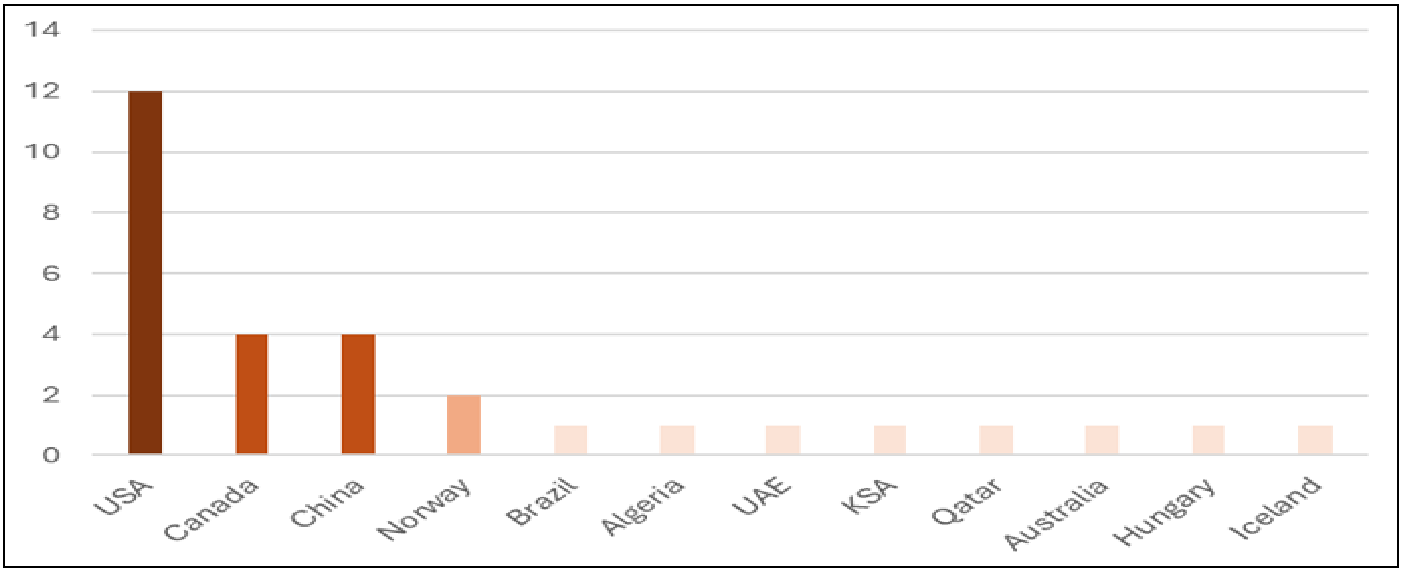

Fig 2 Number of Operational Commercial CCS Facilities in Different Countries
(Source: [25])

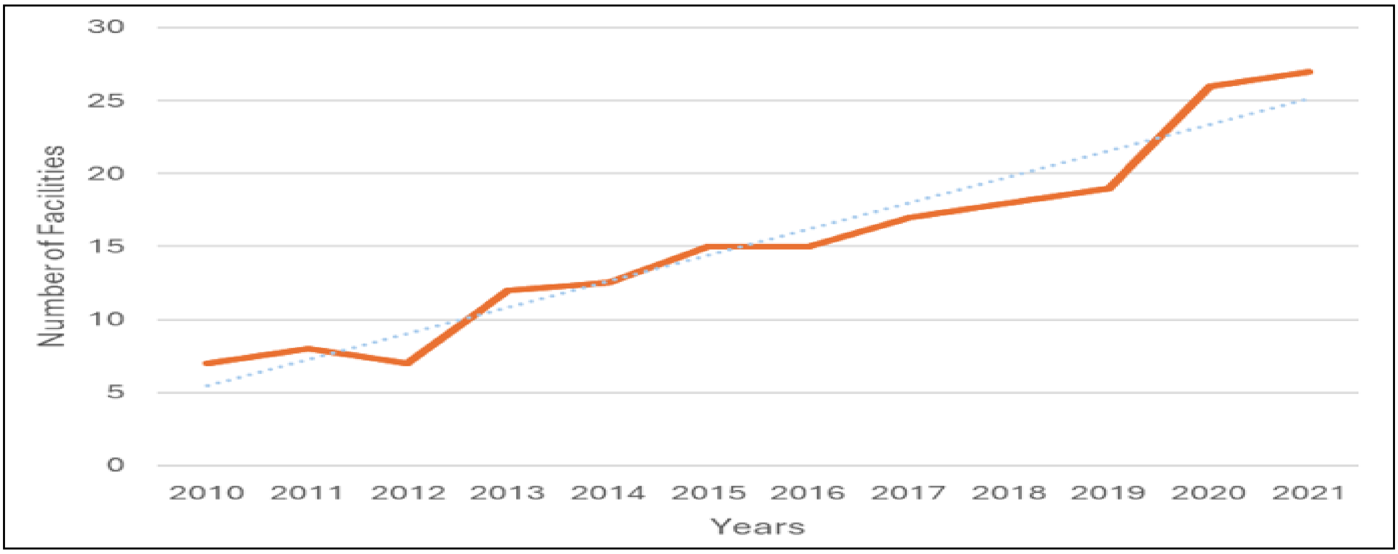

Fig 3 Global Number of Facilities Over the Years 2010–2021
(Source: [25])

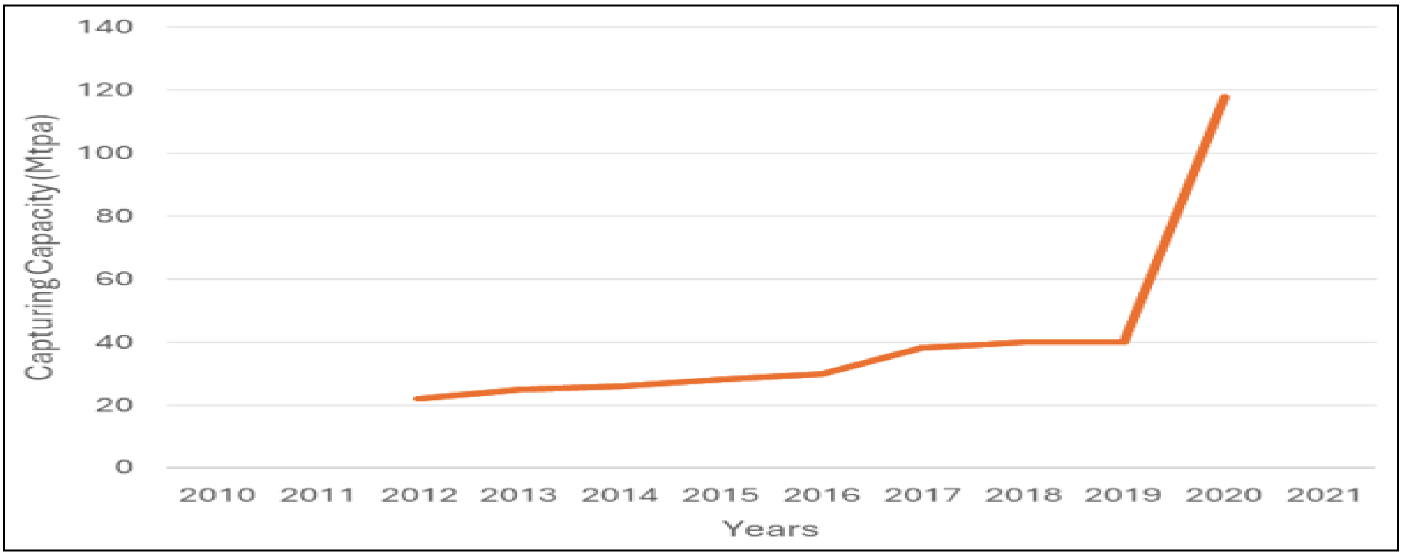

Fig 4 CO_2 Capturing Capacity Over the Years 2012- 2021 (Adapted from [24, 26]).

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D. Challenges Facing Low-Carbon Hydrogen Production

There are a number of different types of hydrogen that have the potential to be included in the low carbon economy. These include green hydrogen, which is created by electrolysis using renewable power, blue hydrogen from fossil fuel sources utilising CCUS technology, and grey hydrogen from fossil fuel sources that does not emit carbon dioxide. Nevertheless, there are a few obstacles that need to be overcome in order to produce these three varieties of low-carbon hydrogen at the moment, which are likely to have an impact on the future decarbonisation objectives.

➢ *Green Hydrogen*

One of the most important premises of the low-carbon hydrogen economy is that hydrogen should be relatively inexpensive to provide. Green hydrogen, on the other hand, is now linked with an expensive price tag. Due to the fact that it requires a complicated multi-component system, green hydrogen generation technology has not yet been made accessible with suitable efficiency and cost [27, 28]. CESAR, which stands for Canada Energy Systems Analysis Research, is a non-profit organisation that focusses on energy and sustainability. According to their estimation, in order for hydrogen to be cost competitive with wholesale diesel prices, the price of hydrogen must be lower than US$2.6/kg H2 [29]. The price of green hydrogen is often too expensive to make it feasible for it to be used on a widespread scale. There is a possibility that the price of green hydrogen will not drop to an acceptable level until the 2030s, as stated by Yu et al. [30].

Several distinct variables have an impact on the cost of environmentally friendly hydrogen. One of the most important considerations is the expense of electrolysis, which is the method of generating hydrogen from water by using renewable energy. At the present time, the overall capacity of electrolysis throughout the globe is restricted. According to Da Silva Veras et al. [31] and Liu et al. [32], the incorporation of electrolysis into practical applications is accompanied by high production costs and significant energy needs. The cost of hydrogen can be reduced by mature technologies, particularly when they are combined with electrolysis-based technologies [33]. In the future, electrolysis-based advancements will be required.

The price of green power that is used in the electrolysis process is the second most important aspect that has an effect on the cost of green hydrogen. The price of green hydrogen is directly proportional to the cost of green power, which is the most significant ingredient. Ayodele and Munda [34] state that the fast decline in the cost of solar and wind power has the potential to cut the price of green hydrogen. Additionally, the International Energy Agency (IEA) states that the cheap cost of green energy will encourage more prospective end users to pay careful attention to green hydrogen. Nevertheless, the rates of green power are still too expensive at the moment. When it comes to the widespread implementation of green hydrogen, the most important factor is the reduction in the cost of renewable power over the long term. For the purpose of lowering the cost of renewable energy, it is essential to increase the amount of power generated by wind and solar.

Based on the findings of Nematollahi et al. [35], the proliferation of wind turbines and solar power generating systems provides a number of major benefits. On the other hand, the transition towards wind energy often elicits a certain level of worry and even protest from the people who live in the surrounding area. According to Walker et al. [36], the greatest emphasis has been paid to the health effect, property devaluation, and unfairness that have occurred as a result of the planning and siting process in the province of Ontario, which is of Canadian origin. Furthermore, the proportion of wind energy that is incorporated into the system continues to be a concern. As a result of the high capital cost of wind infrastructure, the generation of hydrogen using wind power is a costly alternative that governments that are concerned about the environment should consider promoting [37]. It is dependent on the meteorological conditions, such as wind speed, wind direction, temperature, and air pressure, which determines the wind resource that is accessible. According to Bigdeli et al. [38], this results in the possibility of wind power being unclear and has a substantial impact on the cost of green hydrogen. Intermittency is a challenging issue to deal with, despite the fact that solar energy is the most plentiful and long-lasting kind of energy. Furthermore, since it necessitates the provision of extra components, it raises the cost of the hydrogen that is produced [33].

➢ *Blue Hydrogen*

In most cases, the price of coal or natural gas is the primary factor that determines the price of blue hydrogen. In addition, the cost of collecting, reusing, or storing carbon dioxide has an impact on the level of blue hydrogen that is available for purchase. In Canada, the price of blue hydrogen may vary anywhere from 0.99 to 2.05, setting it apart from both black hydrogen and grey hydrogen in terms of its price. The development of blue hydrogen as a transition solution is now confronted with a number of problems. These challenges include the fact that the CCUS technology is not yet fully developed, that the CCUS technology is expensive, and that the efficiency of carbon dioxide capture is poor [39].

First and foremost, the immaturity of the CCUS technology presents a difficulty for large-scale blue hydrogen production. Despite the fact that there are several CCS initiatives that have been successful, the process is generally difficult [40]. There are now 43 significant carbon capture and storage projects throughout the globe, with 18 of them already operational, as stated in the global CCS report published by the Global Carbon Capture and Storage Institute in 2018. The United States of America is home to ten of them, Canada is home to three, Norway is home to two, China is home to one, and the other three are located in other parts of the globe. Due to the fact that the CCUS technology is still in its early phases of technological maturation and has a high operational energy consumption, it will need more applications on a wide scale in the future. However, the relationship between carbon dioxide transport and the development of CCUS on a big scale is still weak

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[41]. Carbon dioxide transport is a crucial requirement for the development of CCUS on a large scale.

The second issue is that the CCUS technology is associated with a high cost. During the beginning stages of the project, the investment expenses are quite large, and all of them are considered to be sunk costs. This is something that discourages the majority of businesses. In spite of the fact that the capital cost of a blue hydrogen plant along with CCUS is about half of the cost of an electrolytic cell plant at the moment. On the other hand, as time goes on as the cost of renewable energy decreases and the price of carbon increases, the price of green hydrogen will decrease, which will result in blue hydrogen being less competitive. According to Chapman et al. [42], the long-term decrease in costs associated with renewable energy and the possibility of developing complementary renewable infrastructure are both reasons that strongly discourage investment in CCUS.

According to Wang et al. [43], the present CCUS technology is not yet completely mature in terms of its deployment in commercial settings because of its high cost.

The efficiency with which carbon dioxide is captured is still another significant obstacle for blue hydrogen. By using CCUS technology, it is possible to lessen the amount of carbon dioxide emissions that are created by hydrogen that is derived from fossil fuel sources. As a result, the carbon footprint of an automobile may be greatly decreased. We can observe that the CO2 intensity of hydrogen generation from natural gas or coal with CCUS is 1 or 2.4 kilogrammes of CO2 per kilogramme of hydrogen by looking at Table 2. The carbon emissions produced by blue hydrogen are lower than those produced by black hydrogen and grey hydrogen. On the other hand, it continues to produce carbon dioxide emissions since there are still some residual emissions that cannot be resolved by direct elimination. With an estimated leakage of between 5 and 15 %, the synthesis of blue hydrogen does not result in zero carbon. Within the range of 85 to 90 %, the steam methane reforming (SMR) process may be carried out with the collection of carbon dioxide. There are indications that the CO2 capture potential of autothermal reforming (ATR) may be more than 90% [44]. This is because ATR has a bigger capacity for trapping carbon dioxide. Blue hydrogen is associated with a significant amount of uncertainty about the possible effects it might have on the environment [45]. The generation of blue hydrogen on a large scale will result in the discharge of millions of tonnes of emissions all year long. In light of this, environmentalists in Europe, Australia, and other parts of the world are expressing their worry about the emissions that are associated with blue hydrogen.

- *Grey Hydrogen*

The economy of Canada is one of the most carbon intensive and energy intensive than any other economy in the world. Canada has a total of 170 billion barrels of oil reserves in addition to its 2 trillion barrels of oil reserves. In light of this, 8.5% of Canada's oil reserves that are currently in existence are judged to be commercially recoverable. By combining its abundant oil sands with its geological CO2 storage capability, Canada may increase its worldwide leadership in hydrogen production by using the grey hydrogen production technology. This would allow Canada to continue to be the leader in the field [46]. Additionally, it will stimulate economic development and the creation of new employment. Although the grey hydrogen technology offers a number of significant benefits for the future low-carbon hydrogen economy, it is currently in the pilot production stage since it is a relatively new technology. It is possible that the development of grey hydrogen as a transition solution will be up against three primary obstacles [46].

Table 2 CO2 Intensity of Hydrogen Production.

Kg CO2/kg H2			
Black hydrogen	Grey hydrogen	Blue hydrogen (Coal with CCUS, 90% capture rate)	Blue hydrogen (Natural gas with CCUS, 90% capture rate)
20	8.5	2.4	1

Source: [5]

The first one is the difficulty that comes with producing on a huge scale. The generation of grey hydrogen is still in its early stages due to the fact that it is a relatively new low-carbon technology. The development of grey hydrogen faces a significant challenge in the form of the question of how to carry out production on a big scale. In order to scale up grey hydrogen production, it is necessary to promote the technology behind grey hydrogen, raise the amount of money invested in grey hydrogen production, and establish commercial infrastructure for the grey hydrogen sector [30].

Concern about the environment is the second obstacle to overcome. In the production wells, the water-gas shift reaction takes place at temperatures higher than 350 degrees Celsius. grey hydrogen is produced underground. It is probable that the general population is worried about the potential effects that this high temperature may have on the ecosystem. There is no carbon dioxide released into the atmosphere during the creation of grey hydrogen. Despite the fact that geological carbon dioxide storage is an efficient method for lowering carbon emissions, there are concerns about its safety and the environmental dangers that should be taken into consideration. Increasing the acidity of water, disrupting the biological balance that existed before, releasing carbon dioxide into the atmosphere, and having an impact on the health of people in the surrounding area are all possible risks associated with the geological storage of carbon dioxide [30].

The last obstacle is opposition from the general population. There is a connection between this difficulty and the environmental concern. It is possible that people are

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concerned about the influence that the grey hydrogen production technique will have on the environment since the general public does not know too much about it. In addition, an increasing number of people believe that green hydrogen is the most promising way for producing hydrogen. As a result, the general people would probably favour the production of green hydrogen. There is a possibility that the public may oppose grey hydrogen. The reluctance of the general public is anticipated to become a significant obstacle in the way of the commercialisation of grey hydrogen technology. Advocates of the grey hydrogen technology have a responsibility to increase the level of societal acceptability of the generation of grey hydrogen [30].

IV. CONCLUSION

This paper highlights the essential function of carbon capture technology in synchronising the hydrogen economy with international climate objectives. The research indicates that while fossil-based hydrogen generation is the prevailing technology, its considerable carbon footprint may be significantly reduced with the incorporation of CCUS, establishing a feasible "blue" hydrogen route. The analysis of carbon capture techniques reveals that each method—post-combustion, pre-combustion, and oxyfuel combustion—presents unique benefits and obstacles, with retrofit capability serving as a significant advantage for prompt emissions mitigation in current infrastructure.

Nonetheless, the trajectory ahead is laden with obstacles. Blue hydrogen encounters challenges with the expenses and technical readiness of carbon capture, utilisation, and storage (CCUS), remaining emissions, and the need for comprehensive CO_2 transportation infrastructure. Simultaneously, green hydrogen, although being a zero-carbon alternative, is now impeded by elevated production costs, the variability of renewable energy sources, and the need for substantial improvements in electrolyser technology and scalability.

Consequently, a realistic and multifaceted approach is necessary. Blue hydrogen, underpinned by effective CCUS, is an essential transitional strategy for the near-term decarbonisation of the existing hydrogen supply, particularly in sectors such as refining and fertiliser manufacturing. Concurrently, continuous investment, research, and policy assistance are necessary to reduce prices and enhance the deployment of green hydrogen. A diverse portfolio that integrates blue hydrogen as an intermediary and green hydrogen as the ultimate objective is essential for a successful and sustainable transition to a low-carbon hydrogen economy.

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