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Review Article

CCUS integration in hydrogen production: Technological advances, sectoral applications, and future perspective

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ABSTRACT

The integration of carbon capture, utilization and storage (CCUS) technologies into hydrogen production is gaining prominence as a transitional solution to reduce emissions in the energy sector. This study explores the technical, environmental, and economic dimensions of blue hydrogen production, which is based on natural gas reforming methods such as steam methane reforming (SMR) and autothermal reforming (ATR) combined with CCUS. While grey hydrogen has a high carbon footprint, blue hydrogen significantly lowers emissions, achieving reductions of up to 90% depending on carbon capture efficiency. The research also compares various CCUS technologies including post-combustion, pre-combustion, and oxy-fuel combustion, alongside emerging alternatives like membrane separation and chemical looping. A techno-economic analysis highlights the trade-offs between capture efficiency, energy demand, cost, and scalability. Global and national hydrogen strategies, including Türkiye's National Hydrogen Strategy, are examined in terms of CCUS integration potential. The study concludes that although challenges such as infrastructure, cost, and policy remain, CCUS-enabled blue hydrogen plays a significant role in the global energy transition toward net-zero targets.

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Highlights

- Blue hydrogen, when integrated with CCUS, offers up to 90% reduction in CO_2 emissions compared to grey hydrogen.
- Post-combustion, pre-combustion, and oxy-fuel combustion are evaluated as core CCUS technologies for hydrogen production.
- Techno-economic analysis identifies oxy-fuel combustion as the most balanced CCUS method for large-scale industrial applications.
- SMR and advanced catalysts enhance efficiency and carbon reduction in blue hydrogen pathways.
- Türkiye's hydrogen strategy highlights blue hydrogen as a transitional bridge to green hydrogen by 2035.
- Global investment trends and policy tools like carbon pricing and CCfDs are accelerating CCUS deployment in hydrogen sectors.

INTRODUCTION

One of the most important global decisions to prevent climate change is the Paris Agreement and the European Green Deal. These agreements make it necessary to reduce carbon in the energy sector. Today, energy production causes about 73% of global greenhouse gas emissions [1]. This makes the energy sector one of the main reasons for the climate crisis. In this context, hydrogen becomes important because it is a flexible energy carrier and can be produced in different ways [2]. Hydrogen is categorized based on the carbon intensity of its production process. Grey hydrogen is produced from fossil fuels, primarily natural gas, through SMR without any carbon mitigation. Blue hydrogen follows a similar pathway but incorporates CCUS technologies to significantly reduce associated emissions. In contrast, green hydrogen is generated via water electrolysis using renewable electricity, resulting in minimal environmental impact. These classifications reflect the varying environmental performance of hydrogen technologies and emphasize the need for a shift towards low-carbon and renewable options in line with global decarbonization goals. These types show that hydrogen can have very different environmental effects, depending on how it is made. Today, about 95% of hydrogen is produced as grey hydrogen, which uses natural gas with SMR [3]. This method produces about 9–12 tons of CO_2 for every 1 ton of hydrogen [4]. This makes grey hydrogen have a large carbon footprint. Therefore, it is not a clean energy source. To solve this problem, a better method called blue hydrogen is developed. Blue hydrogen uses the same SMR method, but it also includes CCUS technologies. In this way, the CO_2 created during production is either stored underground or used in industry [5]. According to Roy et al. (2025), blue hydrogen can reduce the carbon footprint by 56% to 90%. This means blue hydrogen emits about 3.46 to 8.12 kg CO_2eq per kg of hydrogen [6].

These differences are shown in Figure 1. The figure compares the carbon emissions and capture levels of different types of hydrogen. Grey hydrogen shows the highest emissions, while blue hydrogen shows big improvements depending on the capture rate. Some systems like pale blue hydrogen or floating PV-supported hydrogen even have negative emissions [6].

In another study, Zhang et al.[7] examined the technical and economic development of large-scale blue hydrogen production. They showed that methods like ATR and SMR can reduce total emissions when combined with carbon capture. They also said that efficiency, production scale, and carbon pricing are important for making blue hydrogen more competitive in the market. Today, many large blue hydrogen projects are being developed. For example, the Quest Carbon Capture and Storage Project in Canada captures 1 million tons of CO_2 every year and stores it underground [8]. Also, a report by Honeywell and Topsoe (2024) shows that SynCOR^{TM} ATR technology and cryogenic CO_2 separation can produce hydrogen efficiently with low carbon [9]. Khan et al. [10] made a review about blue hydrogen production from natural gas. They said that blue hydrogen is a low-carbon energy solution. Their study explained that the efficiency of carbon capture, methane leaks, and infrastructure planning are all very important. They also showed how regional differences and government support affect the success of these projects.

On the other hand, Howarth and Jacobson [11] say that methane leaks during natural gas production and transport may reduce the benefits of blue hydrogen. Because of this, we must carefully manage carbon capture systems, underground storage, and the natural gas supply chain. Also, according to the International Energy Agency (IEA-2023),

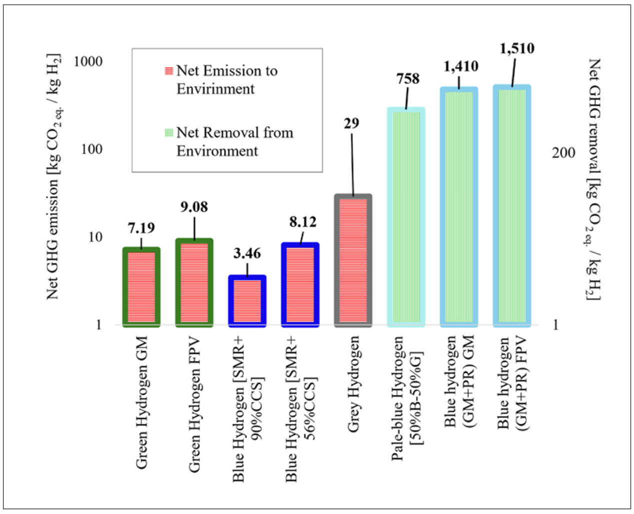

Figure 1. Comparison of Carbon Emissions and Capture Rates of Hydrogen Production Methods [6].

the world plans to reach 40 million tons of blue hydrogen per year by 2030. This can reduce global CO_2 emissions by about 400 million tons [1]. Countries like the European Union (EU), United States of America (USA), and Japan see blue hydrogen as a priority for energy security and low-carbon industry. For example, Germany wants to build 10 Gigawatt (GW) of electrolysis capacity and grow its blue hydrogen sector by 2030 [3]. In Türkiye, the National Hydrogen Strategy (2023) says that by 2035, 70% of hydrogen will be green. But during the transition period, using natural gas infrastructure and CCUS technologies makes blue hydrogen very important [12].

This study focuses on blue hydrogen as a key solution to reduce carbon in energy systems. It will evaluate the technical, economical and environmental results of CCUS technologies in blue hydrogen. The study will also examine how Türkiye and the world can use blue hydrogen in their energy transition policies. Different scenarios will be used to show the emission reduction potential of blue hydrogen. The goal is to give strategic suggestions for global and local energy change.

CCUS TECHNOLOGIES USED IN HYDROGEN PRODUCTION

CCUS technologies primarily entail capturing the emissions of carbon dioxide (CO_2) from industrial processes and fuel combustion, utilizing captured CO_2 for some industrial purposes and then storing the remainder underground securely. The primary technologies for carbon capture are post-combustion, pre-combustion, and oxy-fuel combustion technologies with variations in advantages as well as limitations [13,14].

Post-Combustion Capture

Post-combustion capture captures CO_2 from the flue gases subsequent to the combustion of fossil fuels. It prefers the use of chemical solvents like monoethanolamine (MEA) for CO_2 absorption, making it very compatible with present infrastructure. Some of the advantages are compatibility with present facilities and easy integration with the existing setup (Fig. 2) [13,15]. It is disadvantageous as it is energy-intensive because of the need to regenerate solvents, resulting in high operating costs [15].

Pre-Combustion Capture

Pre-combustion capture converts fossil fuels into synthesis gas (syngas), followed by a reaction that separates CO_2 and hydrogen. This technology is efficient for integrated gasification combined cycle (IGCC) plants, enabling the direct use of hydrogen as a low-carbon fuel [13,16]. Advantages include high efficiency in CO_2 separation and suitability for hydrogen production. Disadvantages include high initial investment and complex infrastructure, limiting its deployment primarily to new plants [16].

Oxy-fuel Combustion

Oxy-fuel combustion involves burning fossil fuels in pure oxygen instead of air, producing a highly concentrated stream of CO_2 after condensing water vapor. Advantages include simplified CO_2 capture and high purity of captured gas [13,17]. However, this method requires energy-intensive oxygen production, usually by cryogenic air separation, which significantly increases operating costs. Additionally, the technology poses challenges such as material corrosion and operational complexity [17].

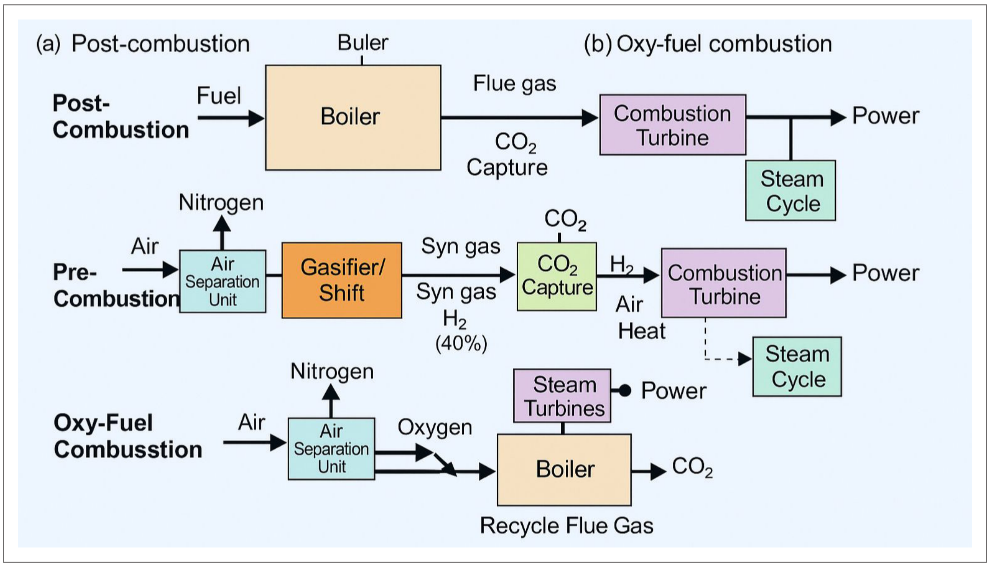

Figure 2. Simplified process diagrams of major CO_2 capture methods: **(a)** Post-combustion, **(b)** Pre-combustion, **(c)** Oxy-fuel combustion. (Redrawn and adapted by the authors based on source [63]).

Alternative Technologies

Emerging CCUS technologies include membrane-based separation, chemical looping combustion (CLC), cryogenic separation, ionic liquid absorption, electrochemical capture, and solid sorbent adsorption (e.g., metal-organic frameworks (MOFs), zeolites). These methods typically offer lower energy requirements and smaller environmental footprints compared to conventional methods, although they often require further development to become economically feasible at scale [18,19].

CCUS Implementation in Türkiye

Türkiye has shown increasing interest in CCUS technologies, particularly after ratifying the Paris Agreement and setting a net-zero emissions target for 2053 [20]. Although commercial-scale deployment is currently limited, TÜBİTAK-supported national projects increasingly focus on CO_2 conversion into value-added products such as biofuels and minerals [20,21]. The EU's Carbon Border Adjustment Mechanism (CBAM) further encourages Türkiye to develop CCUS infrastructure in alignment with both climate and trade goals [14,21].

However, the discussion on Türkiye's CCUS potential has so far remained superficial. Specific data regarding regional CO_2 storage capacities, techno-economic feasibility studies, and measurable outputs from TÜBİTAK-funded or other national pilot projects are currently underrepresented in the literature. For instance, regional geological surveys conducted by MTA and TÜBİTAK suggest that formations such as the Tuz Gölü basin and Diyarbakır–Batman region may offer cumulative CO_2 storage potentials exceeding 1.5 Gt [22,23]. Additionally, the TÜBİTAK 1001 Project titled "Integrated Carbon Capture and Bio-methanation in Anaerobic Systems" (Project Code: 120Y156), as well as Borusan's pilot CO_2 mineralization facility in Gemlik, have reported early techno-economic data including capture costs below $60/ton CO_2 and energy penalties under 15% [24,25]. Including such information provides a more comprehensive perspective on Türkiye's readiness and potential for CCUS deployment and integration into national decarbonization strategies.

Global Implementation of CCUS

Several countries have advanced CCUS deployment. Notable examples include the Boundary Dam project in Canada, Petra Nova in the USA, and Sleipner in Norway—demonstrating real-world feasibility and climate benefits [26,13]. However, challenges persist regarding cost, infrastructure, and verification of long-term storage. For Türkiye, proactive industrial collaboration and supportive policy frameworks will be key to aligning with international climate and economic targets.

FUTURE PLANS IN THE HYDROGEN PRODUCTION SECTOR

Hydrogen production is rapidly evolving as countries pursue low carbon pathways to meet climate goals. Green and blue hydrogen, in particular, are emerging as key tools in global decarbonization efforts. The sector's long term viability depends not only on innovation but also on strong policy support, infrastructure investment, and financial incentives. This section outlines the future direction of hydrogen production, emphasizing global targets, strategic frameworks, and links to carbon reduction technologies like CCUS.

Strategic Roadmaps and Global Alignment

In line with the Paris Agreement and COP commitments, many nations have introduced national hydrogen plans with clear emission reduction goals and production targets. These roadmaps increasingly integrate hydrogen across sectors such as energy, transport, and industry, reflecting a shared vision of its role in a sustainable energy future.The International Energy Agency (IEA) projects that global hydrogen demand could reach 530 million tonnes by 2050 under its Net Zero Emissions (NZE) scenario, with more than 60% produced from renewable sources [27] as illustrated in Figure 3. The European Union (EU), through its Hydrogen Strategy and REPowerEU plan, aims to install 40 GW of electrolyzer capacity within its borders by 2030 and produce 10 million tonnes of renewable hydrogen annually. This will be complemented by an equivalent volume of hydrogen imports from partner countries. National strategies mirror this ambition. Germany plans to reach 10 GW of electrolyzer capacity by 2030, while France and Spain are targeting 6.5 GW and 4 GW, respectively [28]. In Asia, Japan's Green Growth Strategy sets the goal of establishing a full hydrogen supply chain by 2030, supported by substantial public investment. China, the world's largest hydrogen producer, is actively investing in blue and green hydrogen projects, particularly in industrial hubs. Australia and the United States are also leading the transition. Australia aims to develop up to 50 GW of electrolyzer capacity, positioning itself as a global hydrogen exporter [29], while the U.S. government has initiated the Regional Clean Hydrogen Hubs (H_2Hubs) program with an $8 billion budget under the Bipartisan Infrastructure Law [30].

Capacity Targets and Infrastructure Development

The scalability of hydrogen production relies on a dramatic expansion of electrolyzer manufacturing, renewable electricity generation, water supply, and transport logistics. For instance, the IEA estimates that reaching global decarbonization targets will require the deployment of over 850 GW of electrolyzers by 2050, a more than 100-fold increase from current levels [30]. Countries are accordingly investing in grid upgrades, port facilities, hydrogen pipelines, and hydrogen-ready industrial zones [31].

In the EU, initiatives such as the European Hydrogen Backbone (EHB) project propose the development of over 40,000 kilometers of dedicated hydrogen transport pipe-

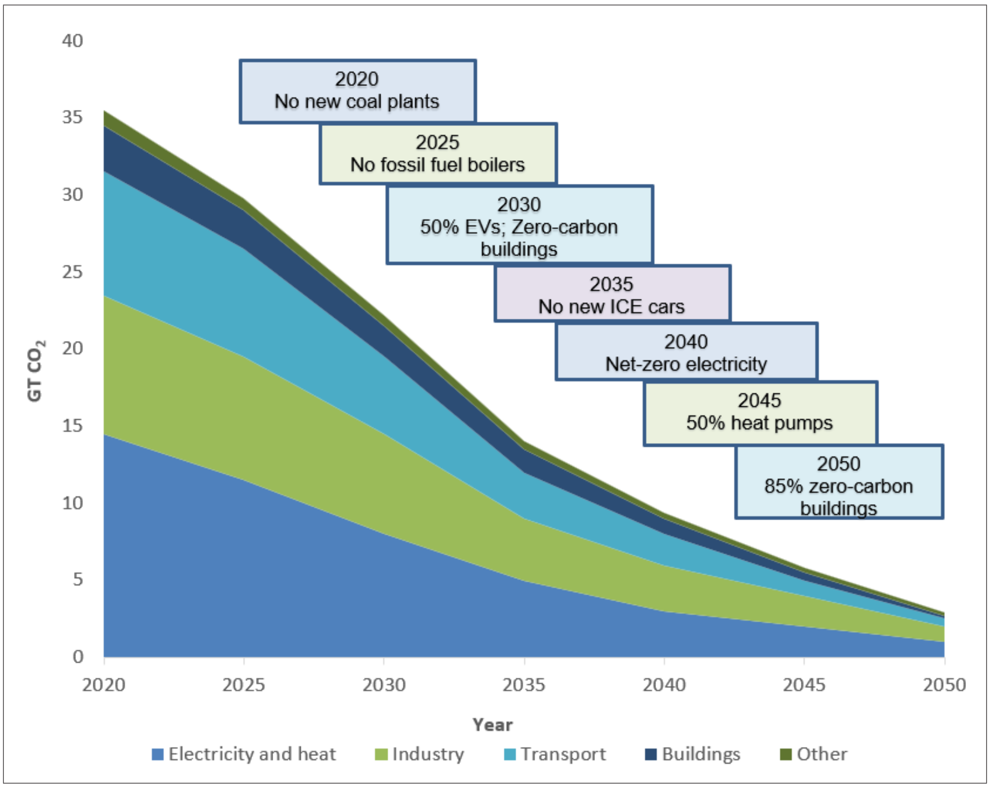

Figure 3. IEA – Net Zero 2050 Roadmap [30].

lines across 28 countries by 2040 [32]. Similarly, Germany is advancing a Hydrogen Core Network that will connect production sites to industrial demand centers. In theUSA, the H_2Hubs are designed not only to establish regional hydrogen markets but also to enable cross-sector integration between industry, mobility, and power generation [30].

Policy and Financial Mechanisms

The realization of hydrogen's potential depends heavily on economic viability and policy support. A variety of mechanisms have been introduced to stimulate investment and de-risk early-stage projects. In the EU, the Emissions Trading System (EU ETS), launched in 2005 and revised in 2023, has raised the cost of carbon to over €85 per tonne, improving the competitiveness of low-carbon hydrogen [33]. Innovation Funds, State Aid Guidelines, and Carbon Contracts for Difference (CCfDs), introduced gradually since 2020, further incentivize green and blue hydrogen production by guaranteeing revenue streams or offsetting operational costs. In the U.S., the 45V production tax credit, introduced under the Inflation Reduction Act (IRA) in 2022, provides up to $3/kg of clean hydrogen produced depending on life-cycle emissions, effectively making green hydrogen cost-competitive with fossil-derived hydrogen [30]. In addition, the 45Q tax credit, first enacted in 2008 and expanded in 2022, provides $85 per tonne of CO_2 captured and stored, directly supporting blue hydrogen projects integrated with CCUS [32].

Asia is also rapidly mobilizing capital. Japan has pledged $13.5 billion in subsidies for hydrogen infrastructure since 2021, while South Korea and China are combining industrial policy with public-private partnerships to scale hydrogen supply chains. Financial institutions are also stepping in; multilateral banks and green investment funds are increasingly supporting hydrogen projects in emerging economies.

Integration with CCUS and Transition Pathways

Although green hydrogen remains the ultimate objective, blue hydrogen produced through SMR combined with CCUS is widely viewed as a practical transition solution. As noted by the Hydrogen Council (2023), blue hydrogen can cut CO_2 emissions by up to 90% compared to conventional grey hydrogen, making it particularly relevant for gas-rich regions [34].

Countries such as Canada, Norway, and the UK have incorporated blue hydrogen into their national strategies, taking advantage of existing gas networks and geological CO_2 storage options. Flagship CCUS projects like Norway's Northern Lights and the UK's Net Zero Teesside are setting examples by integrating hydrogen production with advanced carbon capture systems. Additionally, alternatives like turquoise hydrogen from methane pyrolysis and hydrogen from nuclear-powered electrolysis are gaining attention as region-specific, low-carbon solutions that may bridge the gap toward full decarbonization.

POTENTIAL OF CCUS TECHNOLOGIES IN THE HYDROGEN PRODUCTION SECTOR

Technological and Operational Improvements

Currently, hydrogen is predominantly produced from fossil fuels, namely brown and grey hydrogen. According to the International Renewable Energy Agency (IRENA-2018), approximately 48% of global hydrogen production is derived from natural gas, 30% from oil, and 18% from coal. Only about 4% is generated through electrolysis using electricity from the grid or renewable energy sources, which is referred to as green hydrogen. Hydrogen is currently utilized across various industrial sectors, including chemical production (e.g., methanol, ammonia), refining processes (such as hydrogenation and hydrocracking), metal processing, aerospace, food, and glass industries [35]. In addition to methanol synthesis, hydrogen plays a pivotal role across a range of industrial processes where its high reactivity and energy density are leveraged. Ammonia production, primarily via the Haber–Bosch process, remains one of the most hydrogen-intensive applications globally. This process involves the reaction of nitrogen, extracted from ambient air, with hydrogen under elevated pressures and temperatures in the presence of an iron-based catalyst, and it is fundamental to global fertilizer manufacturing [36]. In the petroleum refining sector, hydrogen is extensively employed in hydrocracking and hydrotreating units to upgrade heavy hydrocarbon fractions, eliminate impurities such as sulfur, nitrogen, and metals, and generate cleaner transportation fuels. Moreover, hydrogenation reactions are widely utilized in the chemical industry to saturate unsaturated organic compounds, thereby enhancing the chemical stability, performance, and shelf life of end products [37]. These hydrogen-driven applications are underpinned by mature and well-established technologies characterized by high Technology Readiness Levels (TRLs). As the global energy system transitions toward low-carbon solutions, these conventional hydrogen-based processes are increasingly being re-evaluated for integration with carbon capture technologies and green hydrogen alternatives to mitigate their environmental impact and contribute to industrial decarbonization [38,39].

Among its various uses, methanol is a "bridge" molecule that enables both the chemical fixation of CO_2 and the practical transportation and storage of H_2. This dual function makes it a strategic intermediate for both carbon management and renewable energy storage/distribution. Methanol (MeOH) is recognized as a key feedstock in the petroleum, chemical, and energy industries. It serves as a fuel in fuel cells, gasoline blending, combustion engines, and marine applications, while also acting as a precursor in the production of acetic acid, formaldehyde, olefins, and synthetic fibers. Owing to its versatile applications, global demand for methanol increased by approximately 4% between 2018 and 2023 [40]. Additionally, due to growing concerns about climate change and increasing interest in hydrogen as a clean energy carrier, methanol has emerged as a viable medium for hydrogen storage and transport. It can be synthesized via a single-step catalytic reaction using CO_2 and H_2 as reactants, allowing for the chemical fixation of CO_2. When derived from captured CO_2 emissions, the resulting product is referred to as blue methanol. Global methanol demand is projected to grow from 100 million tonnes in 2020 to 500 million tonnes by 2050 [35, 40]. Methanol can be classified as either high or low carbon intensity, depending on the feedstock and associated emissions. Methanol produced from fossil fuels such as coal and natural gas, without carbon capture or renewable inputs (i.e., brown and grey methanol), is typically categorized as high-carbon. In contrast, methanol derived from renewable energy, fossil sources with carbon capture, or a combination of both (green and blue methanol), is regarded as a low-carbon alternative.

Conventional methanol production is primarily based on SMR, where synthesis gas (H_2, CO, and CO_2) is generated from natural gas. SMR is the most common and cost-effective method for hydrogen production, used by approximately 50% of global hydrogen production facilities. The resulting synthesis gas can be directly utilized in methanol synthesis, potentially meeting up to 90% of global methanol demand. The technology has reached a high maturity level, reflected in its Technology Readiness Level (TRL) of 9 [41]. In the SMR process, methane (CH_4) reacts with steam at high temperatures to produce H_2 and CO. This is followed by the Water-Gas Shift (WGS) reaction, where part of the CO is converted into CO_2 while additional hydrogen is produced (Figure 4). The resulting gas mixture, rich in H_2 and CO_2, is purified using physical or chemical separation techniques and then used for methanol synthesis in appropriate ratios. The proposed process enables the simultaneous production of both H_2 and CO_2 from natural gas, which are directly utilized for methanol synthesis. This way, carbon from fossil sources is chemically bound in the product rather than being released into the atmosphere, exemplifying an effective application of CCUS technology.

Conventional SMR operates at 800-900 °C and 3-25 bar, requiring partial combustion of natural gas to provide the heat. This reduces energy efficiency and generates additional CO_2 emissions. Electrically heated SMR (e-SMR), on the other hand, reforms hydrocarbons directly with electrical energy by heating the catalytic surfaces by resistance or induction. Using electrical heat instead of combustion eliminates CO_2 emissions from combustion and significantly reduces the carbon intensity of the system [42]. The syngas from the SMR unit is typically directed to gas separation units such as membrane systems, Pressure Swing Adsorption (PSA) or amine absorption, where H_2 and CO_2 are separated into separate phases.

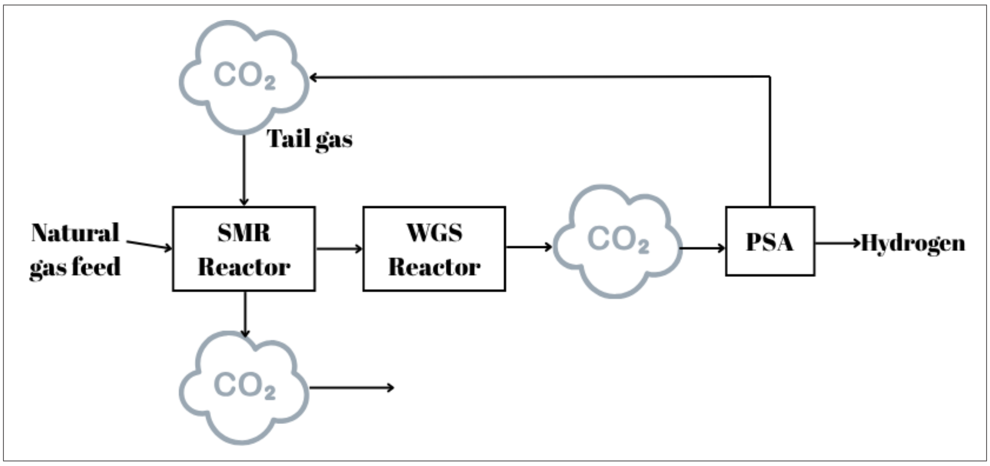

Figure 4. SMR based blue hydrogen and CO_2 production [64].

The new generation of zeolite-based membrane technologies in particular offer high H_2 purity and enable the installation of compact integrated systems, significantly improving operational efficiency. Obtaining the separated CO_2 in a separate phase makes it possible to use this gas directly in chemical bonding or capture processes [43, 44]. The CO_2 + H_2 route for methanol synthesis is both kinetically and thermodynamically more challenging compared to the conventional method involving CO; therefore, special catalysts are required. Since the classical $Cu/ZnO/Al_2O_3$ system can show instability at high pressure and temperature, $ZnZrO_x$, In_2O_3-ZrO_2 or Ga-doped alternatives have been developed. For example, In_2O_3-based catalysts exhibit up to 80% CO_2 conversion and over 90% methanol selectivity at 240-270 °C and 30-50 bar conditions. Catalyst choice plays a key role in operational improvements as it directly affects the energy requirements of the process [45]. Since methanol synthesis is exothermic, it is critical to control the heat generated; otherwise catalyst sintering, loss of selectivity or carbon deposition can occur. Micro-channel reactors offer both safe and low energy consumption methanol production using blue hydrogen, with compact designs that provide fast and homogeneous heat transfer [46]. Heat and energy integration is critical in integrated SMR-methanol plants; up to 800 °C synthesis gas heat from the SMR is reused in stages such as the reboiler of the methanol synthesis unit and preheating of feed steam, increasing energy efficiency. In addition, the energy requirements of auxiliary systems such as CO_2 compressors, H_2 transport lines and product condensation units are minimized thanks to the integrated design. Process simulations in the literature show that total process efficiency can be increased to over 70% with such heat recovery strategies [47].

Feasibility and Scalability

The success of proposed technologies to achieve carbon emission reduction targets should not only be limited to their technical feasibility, but should also meet the conditions of economic sustainability and compliance with market conditions. Although CO_2-methanol synthesis integrated with SMR-based hydrogen production seems technically feasible in the short term, its economic feasibility varies significantly depending on project parameters, regional energy costs and carbon regulations. In this context, the investment costs, operating costs, production efficiency and economic return models of the system should be examined in detail.

As presented in Table 1., SMR plants at TRL 9 can produce hydrogen at capacities ranging from 200-500 tons per day, while ATR and Partial Oxidation (POx) plants can produce hydrogen at capacities ranging from 500-1000 tons per day, providing flexible solutions for both medium and large industrial needs.

SMR processes can be scaled up above a base efficiency of 83% with existing waste heat recovery strategies, while costs ranging from USD 0.9-1.8 per kilogram are supported by the widespread availability and low price of natural gas. Moreover, the availability of global natural gas pipeline and storage infrastructure reduces the need for large-scale infrastructure investment in the commissioning of new plants, lowering capital expenditures (CAPEX) and shortening the payback period. With these characteristics, natural gas reforming technologies stand out as the "what works" option that offers the highest maturity, efficiency, and cost-effectiveness. In the coming period, blue hydrogen production with waste heat integration and carbon capture applications will also become significantly widespread.

RESULTS AND DISCUSSION

Technical Performance Comparison

The technical evaluation of the three selected CCUS technologies—Post-combustion MEA absorption, polymer membrane separation, and oxy-fuel combustion—is summarized in Table 2. MEA absorption achieved the highest capture rate (85–95%) [49] but at a high energy penalty (3.6–3.8

Table 1. Comparison of hydrogen production technologies [41,48].

Technology	Raw material	TRL	Efficiency (%)	Scalability	Levelized Cost of Hydrogen (LCOH)
SMR	Natural gas	9	~83	200–500 ton/day	0.9–1.8 $/kg
ATR	Natural gas	9	~90	500–1000 ton/day	Not determined
POx	Natural gas and waste oil	9	70–80	500–1000 ton/day	Not determined
Gasification	Coal	9	Not determined	500–800 ton/day	1.6–2.2 $/kg
Pyrolysis	Oil and coal	Not determined	Not determined	50 ton/day	2.2–3.4 $/kg
Alkali electrolysis (AE)	Water + Electricity	9	63–71 (cell) 51–60 (system)	<70 ton/day	2.6–6.9 $/kg
Proton conducting membrane electrolysis (PEM)	Water + Electricity	9	60–68 (cell) 46–60 (system)	<300 ton/day	3.5–7.5 $/kg
Solid oxide electrolysis cell (SOEC)	Water + Electricity	6–7	100 (cell) 76–81 (system)	Not determined	5.0–8.5 $/kg

Table 2. CAPEX and O&M cost comparisons.

Process	CAPEX (€/tCO_2)	O&M (€/tCO_2)	Usage Period (Year)	References
MEA absorption	90–156	41–44	20-30	[49,56]
Polymer membrane	18-44	Not determined	5	[54,56]
Oxy-fuel combustion	30 - 50	15.47	30	[54,55]

GJ/t CO_2) [43] and is fully commercial (TRL 9) [50]. Polymer membranes offered moderate to high capture efficiency (60–95 %) [49] with a lower energy demand (0.7–1.5 GJ/t CO_2) [49] but remain at TRL 7–8 [51], indicating ongoing scale-up challenges. Oxy-fuel combustion provided ~90% capture with an energy load of 200–300 kWh/t O_2 (≈0.72–1.08 GJ/t CO_2 equivalent) [49] at TRL 7 [52]. Although MEA delivers the best capture efficacy, its high energy consumption may limit deployment in energy-intensive sectors. Conversely, polymer membranes and oxy-fuel offer lower energy footprints but require further development or integration to reach full commercialization [53–55].

Economic Assessment

Table 2 presents CAPEX and Operation and Maintenance (O&M) cost comparisons. MEA absorption incurs the highest total cost (90–156 €/t CO_2 CAPEX; 41–44 €/t CO_2 O&M) [49] but benefits from long operational lifetimes (20–30 years) [49]. Polymer membranes exhibit the lowest CAPEX (18–44 €/t CO_2) [56] and minimal O&M—but suffer from short design lives (≈5 years), potentially increasing replacement frequency and total lifecycle costs [54]. Oxy-fuel combustion sits between the two (30–50 €/t CO_2 CAPEX; 15.5 €/t CO_2 O&M; 30 years lifetime) [54,55]. When normalized over a 20-year period, oxy-fuel demonstrates the most balanced cost

Most Feasible Technology and Sectoral Priorities

Considering both technical and economic metrics, oxy-fuel combustion emerges as the most balanced CCUS option for large-scale industrial emitters. Its moderate capture efficiency (≈90%) [49] and mid-range energy and cost figures make it suitable for cement, steel, and power sectors where high-purity O_2 streams are already used. In contrast, polymer membranes are promising for modular, distributed applications (e.g., small NG-fired turbines) where low energy consumption and compact footprint are critical—even if frequent replacements are required [49]. MEA absorption, while technically proven, is best reserved for schemes with access to low-cost steam or waste heat to offset its high regeneration energy [49]. Among carbon capture technologies, MEA (monoethanolamine) absorption stands out as a mature and well-established method, offering very high CO_2 capture rates and a long operational lifetime. However, its main drawback lies in its high energy consumption and elevated operation and maintenance (O&M) costs [49,50]. Another promising approach is the use of polymer membrane systems, which offer advantages such as low energy demand, low capital expenditure (CAPEX), and compact design. Nevertheless, their short membrane lifespan, scalability challenges, and the fact that they are still at a pre-commercial stage (Technology Readiness Level 7–8) limit their widespread application [49,51-53]. Oxy-fuel combustion technology presents a balanced trade-off between cost and performance. It can be integrated with existing Air Separation Units (ASU) and provides long-term operational stability. On the downside, it requires large volumes of pure oxygen and considerable energy input for ASU operation, which pose significant challenges for practical deployment [54,52,55].

Discussion and Future Perspective

The choice of CCUS technology must align with sectoral priorities. Energy-intensive industries (cement, steel) favor oxy-fuel for its compatibility with high-purity O_2 combustion and stable operation over decades [49,51]. Conversely, distributed power generation and smaller emitters can leverage polymer membranes' low energy footprint and modularity, accepting shorter equipment life [50,51]. MEA absorption remains a benchmark for large post-combustion flue-gas streams where waste heat integration can mitigate its energy costs [49]. Ultimately, a hybrid deployment—combining MEA for base-load capture, membranes for peaking units, and oxy-fuel for new builds—may optimize overall system performance and economic return across diverse industrial applications.

Integrated CCUS technologies are emerging as a key component of the low-carbon energy transition, playing a critical role particularly in the decarbonization of energy-intensive hydrogen-consuming industries. This is mainly because approximately 95% of today's hydrogen is still produced through fossil fuel-based processes [57]. This situation highlights the increasing importance of CCUS technologies in the pursuit of emission reduction targets. In this context, the Shell Quest project in Alberta, Canada demonstrates the technical and economic feasibility of CCUS integration by capturing and injecting underground approximately 1 million tonnes of CO_2 annually through pre-combustion capture in hydrogen production via SMR [58]. Similarly, at the Port Arthur facility in Texas, operated by Air Products, CO_2 released during hydrogen production in refineries is captured and used in Enhanced Oil Recovery (EOR) processes, delivering both climate and economic benefits. The facility has an annual capture capacity of over 1 million tonnes [59].

One of the pioneering initiatives in Europe, the HyNet project in the United Kingdom, aims to capture up to 95% of the CO_2 from blue hydrogen production using natural gas and transport it to offshore storage sites in Liverpool Bay. The project plans to reach an annual capture capacity of 10 million tonnes of CO_2 by 2030 [60]. These examples demonstrate that CCUS technologies can be successfully integrated into hydrogen production processes, enabling the widespread adoption of blue hydrogen. However, high capital costs, infrastructure requirements, and regulatory uncertainties remain significant barriers at this development stage. Despite these challenges, government support, carbon pricing mechanisms, and net-zero commitments are fostering the spread of such investments.

Although there are some barriers at present, the future outlook for CCUS integration technologies holds significant value when considering global energy transition goals. CCUS plays a vital role in reducing CO_2 emissions, especially in grey and blue hydrogen production processes, positioning itself as a bridging technology in the decarbonization of the hydrogen economy [61]. According to the IEA, around 60% of hydrogen must come from low-carbon sources (blue or green) by 2050 to achieve a carbon-neutral energy system, a goal that will largely depend on the widespread deployment of CCUS technologies [27]. Additionally, according to the IEA's 2024 Global Hydrogen Review, approximately 20% of the $3.5 billion USD investment in hydrogen supply projects in 2023 was allocated to CCUS-integrated projects, most of which are concentrated in North America. With increasing CCUS investments, it is projected that up to 60 million tonnes of CO_2 could be captured annually from hydrogen production by 2030 [27]. Nevertheless, cost, infrastructure limitations, and regulatory uncertainties still pose significant obstacles to the widespread adoption of these technologies [62]. On the other hand, the inclusion of CCUS as a core element in strategic hydrogen policies by countries such as China, as well as incentivizing policy instruments like carbon border adjustments, are supporting the future development of these technologies.

CONCLUSION

This study highlights that integrating CCUS technologies into hydrogen production processes can serve as a crucial step in the broader transformation of energy systems. Particularly, the deployment of CCUS within SMR and ATR-based hydrogen production pathways significantly lowers the carbon intensity of hydrogen, providing a realistic and scalable option during the energy transition period. Blue hydrogen, as a result of this integration, presents emission reductions that in some cases reach close to 90% compared to traditional grey hydrogen production.

Different capture methods yield varied technical outcomes. While solvent-based systems like MEA absorption deliver high capture rates, they also introduce notable energy costs. On the other hand, membrane-based systems and oxy-fuel combustion offer operational advantages with lower energy demand, making them suitable for targeted industrial use where energy efficiency is a priority. These technological differences suggest that a mix of capture approaches, tailored to specific sectors, could maximize effectiveness. Another key finding is that using captured CO_2 for methanol synthesis creates additional value, both environmentally and economically. This circular approach supports the green transition by converting emissions into useful chemicals and fuels, reducing reliance on fossil-derived inputs. Countries like Türkiye, which already have established natural gas infrastructure, stand to benefit from this interim strategy. It enables immediate emission cuts while building the technical and institutional foundation for a broader shift to green hydrogen in the long term.

Taken together, the results underscore that CCUS-enabled hydrogen systems can act as a bridge—both technologically and strategically—between today's carbon-intensive landscape and tomorrow's net-zero ambitions. The dual alignment with energy transition pathways and green transition goals positions blue hydrogen as a critical piece of the decarbonization puzzle.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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