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Review

Comprehensive Review of Carbon Capture and Storage Integration in Hydrogen Production: Opportunities, Challenges, and Future Perspectives

Seyed Mehdi Alizadeh [1,*], Yasin Khalili [2] and Mohammad Ahmadi [2]

[1] Department of Petroleum Engineering, College of Engineering, Australian University, West Mishref, Safat 13015, Kuwait
[2] Department of Petroleum Engineering, Amirkabir University of Technology, Tehran 1591634311, Iran; yassinkhalili.pe@aut.ac.ir (Y.K.); m.ahmady@aut.ac.ir (M.A.)
* Correspondence: s.alizadeh@au.edu.kw

Abstract: The growing emphasis on renewable energy highlights hydrogen's potential as a clean energy carrier. However, traditional hydrogen production methods contribute significantly to carbon emissions. This review examines the integration of carbon capture and storage (CCS) technologies with hydrogen production processes, focusing on their ability to mitigate carbon emissions. It evaluates various hydrogen production techniques, including steam methane reforming, electrolysis, and biomass gasification, and discusses how CCS can enhance environmental sustainability. Key challenges, such as economic, technical, and regulatory obstacles, are analyzed. Case studies and future trends offer insights into the feasibility of CCS–hydrogen integration, providing pathways for reducing greenhouse gases and facilitating a clean energy transition.

Keywords: hydrogen; carbon capture and storage (CCS); greenhouse gas emissions; decarbonization; sustainable energy; clean energy carrier

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1. Introduction

Carbon capture and storage (CCS) technologies have emerged as a critical tool for reducing greenhouse gas emissions and mitigating climate change. Recently, there has been a growing interest in integrating CCS with hydrogen production processes to further enhance the environmental sustainability of hydrogen as a clean energy carrier. This comprehensive analysis aims to explore the potential, challenges, and future prospects of combining CCS with hydrogen production [1].

Hydrogen is a pivotal element in the transition to a more sustainable economy, providing a flexible and environmentally friendly substitute for traditional fossil fuels. However, current hydrogen production methods such as steam methane reforming and coal gasification are associated with significant carbon emissions. By integrating CCS technologies into these processes, it becomes possible to capture and store CO_2 emissions, thereby reducing the overall carbon footprint of hydrogen production [2].

1.1. Significance of Hydrogen Production in Decarbonization and Clean Energy Transitions

The integration of hydrogen into energy systems has evolved substantially over the past few decades. In the early 1970s, hydrogen was primarily explored as an energy carrier due to growing concerns about energy security and the oil crisis. However, its widespread application remained limited by technological and economic constraints. During the 1990s, research into hydrogen gained momentum with a focus on its potential to reduce greenhouse gas emissions. Significant advancements in fuel cell technology led to the development of hydrogen-powered vehicles and increased interest in hydrogen as a clean fuel for transportation [3]. The early 2000s witnessed the first commercial deployments of hydrogen fuel cells, particularly in the automotive sector. Companies like Toyota and Honda introduced hydrogen-powered vehicles, and governments worldwide began investing in hydrogen infrastructure [4]. Since 2010, the role of hydrogen has expanded beyond transportation to include industrial applications and energy storage solutions. This period marked the emergence of large-scale projects integrating hydrogen with renewable energy sources, such as wind and solar power, to produce green hydrogen [5]. In recent years (2020s), the global focus on achieving carbon neutrality by mid-century has elevated hydrogen to a prominent position in energy strategies. Countries have announced hydrogen roadmaps, and international collaborations have formed to develop a global hydrogen economy. Recent innovations include the integration of hydrogen into hard-to-decarbonize sectors, such as steel production, cement manufacturing, and high-temperature industrial processes. The incorporation of CCS technologies into hydrogen production processes has also been a crucial development aimed at reducing emissions from traditional hydrogen production methods [6].

Hydrogen generation is crucial for mitigating carbon emissions and advancing clean energy transitions. It serves as a versatile and environmentally friendly energy option that contributes to reducing greenhouse gas emissions and facilitating the integration of renewable energy sources [7]. This analysis examines the significance of hydrogen production in the context of decarbonization and the transition to clean energy:

1. Reducing Greenhouse Gas Emissions: Green hydrogen, produced from sustainable sources, offers an eco-friendly alternative to traditional fuels due to its minimal greenhouse gas emissions during production [8]. By utilizing sustainable electricity to power electrolysis machines that separate water into hydrogen and oxygen, we can significantly reduce carbon emissions across various industries, including transportation, manufacturing, and heating, thereby contributing to the fight against climate change [9].
2. Energy Storage and Grid Balancing: Hydrogen can function as an energy storage solution, enabling the integration of intermittent renewable energy sources like solar and wind power into the power grid [10]. Excess electricity generated during peak renewable energy production periods can be used to create hydrogen through electrolysis. This stored hydrogen can then be converted back into electricity via fuel cells as needed, helping to balance energy supply and demand on the power grid [11].
3. Sector Coupling and Electrification: Hydrogen has the potential to promote sector integration by connecting traditionally separate energy sectors such as transportation, industry, and power generation. By employing hydrogen fuel cells in electric vehicles, for heating purposes, and in high-temperature industrial processes, hydrogen can enable the electrification of sectors that are challenging to decarbonize solely through direct electricity [12]. Several studies have investigated the potential of hydrogen to facilitate sector integration. For example, a recent paper published in *Angewandte Chemie International Edition* [13] highlighted the role of hydrogen in decarbonizing the transportation sector through the use of fuel cell electric vehicles (FCEVs). The authors emphasized the advantages of FCEVs in terms of their longer driving range and faster refueling times compared to battery electric vehicles (BEVs).

   Beyond transportation, hydrogen can also play a crucial role in decarbonizing the heating sector. A study published in *Rare Metals* [14] explored the potential of hydrogen fuel cells for residential and commercial heating applications. The authors found that hydrogen fuel cells can provide efficient and clean heating solutions, with the added benefit of generating electricity as a byproduct. Additionally, hydrogen can be utilized in high-temperature industrial processes such as steelmaking and chemical production. A paper published in *Exploration* [15] discussed the potential of hydrogen as a reducing agent in steelmaking, which could significantly reduce carbon emissions from this energy-intensive industry.
4. Industrial Decarbonization: The industrial sector, which is heavily reliant on fossil fuels for heat and power generation, can benefit substantially from clean hydrogen as a substitute for natural gas or coal [16]. By substituting hydrogen for fossil fuels

in activities like steelmaking, ammonia production, and chemical manufacturing, industries can decrease their carbon footprint and transition towards more sustainable and cleaner production practices [17].

5. International Energy Trade: Hydrogen has the potential to become a globally traded commodity, facilitating the exchange of clean energy between regions with abundant renewable resources and those in need of energy imports [18]. By establishing hydrogen supply chains and infrastructure for international trade, countries can diversify their energy sources, enhance energy security, and promote international cooperation in achieving climate goals [19].
6. Innovation and Technological Advancements: The increasing interest in hydrogen production has driven innovation in electrolysis technologies, storage methods, and fuel cell applications [20]. Research and development initiatives are reducing costs, enhancing efficiency, and expanding the potential uses of hydrogen in various sectors, accelerating the transition towards a cleaner and more sustainable energy infrastructure [21].

1.2. The Role of Carbon Capture and Storage in Reducing Greenhouse Gas Emissions

CCS is a pivotal technology for significantly reducing greenhouse gas emissions by capturing CO_2 from industrial operations or power plants, transporting it to storage locations, and securely storing it underground to prevent its release into the atmosphere [22,23]. This overview outlines CCS and its significance in addressing climate change:

1. Capture: The initial phase of CCS involves the capture of CO_2 emissions from various sources such as power plants, cement factories, or industrial facilities to prevent their release into the atmosphere [24]. Diverse capture technologies, including post-combustion capture, pre-combustion capture, and oxy-fuel combustion, are used to separate and capture CO_2 from the flue gas or exhaust streams of these facilities [25].
2. Transport: Once CO_2 is captured, it must be transported to suitable storage locations for long-term sequestration. CO_2 can be conveyed through pipelines, trucks, ships, or other methods to designated injection sites, where it will be securely stored beneath the ground [26].
3. Storage: In the storage phase, the captured CO_2 is commonly injected deep beneath the Earth's surface into geological formations like depleted oil and gas reservoirs, saline aquifers, or coal seams [24]. These locations provide safe and long-term storage for CO_2, where it is contained in either gaseous or liquid form, confined by impermeable rock formations to prevent any release back into the atmosphere [27].
4. Enhanced Oil Recovery (EOR): In certain cases, carbon dioxide captured through CCS may be utilized for enhanced oil recovery. This process involves injecting CO_2 into oil reservoirs to boost the production of oil [23]. This method not only stores CO_2 underground but also offers a financial incentive for implementing CCS technologies [26].
5. Role in Greenhouse Gas Emissions Reduction: CCS is instrumental in decreasing greenhouse gas emissions by trapping and storing CO_2 that would otherwise escape into the atmosphere [28]. It is considered a critical technology for achieving net-zero emissions targets and combating climate change by assisting industries and power plants in reducing their carbon footprints [28].
6. Technological Advancements: Research and development efforts are currently focused on enhancing CCS technologies to make them more affordable, environmentally friendly, and scalable [29]. Innovations in capture methods, storage techniques, and monitoring technologies aim to improve the overall performance and viability of CCS projects [30].
7. Policy Support and Incentives: Governments, international organizations, and industry stakeholders recognize the importance of CCS in achieving climate goals and reducing emissions [31]. Government support, financial incentives, carbon pricing systems, and regulations are crucial in stimulating the implementation of CCS projects and accelerating the transition towards a sustainable, low-carbon economy [32].

By capturing and permanently storing CO_2 emissions, CCS offers a proven method to reduce greenhouse gas emissions, enhance industrial sustainability, and support global efforts to combat climate change. Integrating CCS into a comprehensive climate change strategy can accelerate the transition to a sustainable future [33]. A visual representation of the various components of CCS and their contributions to mitigating greenhouse gas emissions, as well as the driving forces behind CCS, is provided in Figure 1.

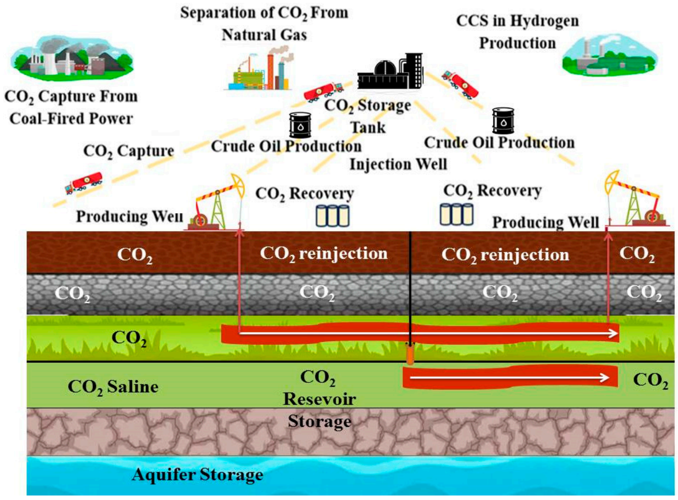

Figure 1. Components of CCS and its impact on greenhouse gas emissions reduction [24].

1.3. The Purpose of This Article

This review paper aims to elucidate the pivotal role of hydrogen generation in mitigating carbon emissions and driving clean energy transitions, as well as the significance of CCS in reducing greenhouse gas emissions. The article will delve into various approaches for producing hydrogen and CCS techniques, investigate how CCS can be integrated into hydrogen production methods, highlight the advantages and opportunities associated with this integration, address the challenges and constraints involved, examine recent advancements and practical examples, and provide a perspective on the future outlook of integrating CCS into hydrogen production.

2. Hydrogen Production Methods

2.1. Exploration of Different Methods of Hydrogen Production

Steam methane reforming (SMR) is a widely used process in large-scale industrial hydrogen production. It involves the high-temperature reaction of natural gas (methane) with steam and a catalyst to generate hydrogen and carbon monoxide.

Catalysts are essential for enhancing the efficiency of hydrogen production processes, particularly in water electrolysis and SMR. Recent advancements have introduced innovative catalysts that significantly improve catalytic activity and reduce energy consumption. Among these, single-atom catalysts (SACs) have garnered significant attention due to their unique properties [34]. Water electrolysis plays a crucial role in producing green hydrogen, especially when powered by renewable energy sources. While the efficiency of traditional electrolyzers has been a subject of research, recent advancements have demonstrated significant improvements in both performance and cost-effectiveness. A study by Zhang et al. (2019) explores novel catalysts and membrane technologies that enhance the electrolysis process, focusing on reducing the energy required for hydrogen production. This research highlights the potential of innovative materials and designs in optimizing water electrolysis, which could provide valuable insights for improving current hydrogen production methods [35]. Single-atom catalysts, which feature metal atoms dispersed on a support surface, maximize the utilization of metal atoms, leading to higher catalytic efficiency and selectivity. According to a study by Zhang et al. (2019), SACs exhibited superior performance in water electrolysis by reducing the overpotential required for the oxygen evolution reaction (OER), a critical step in hydrogen production. Their ability to stabilize single metal atoms on supports like graphene has shown great promise in enhancing catalytic activity while reducing the amount of precious metal needed [35]. Similarly, a more recent study by Zhang et al. (2023) explored the potential of SACs in reforming reactions and hydrogen production. The study found that SACs not only improved reaction rates but also offered greater stability in high-temperature processes such as SMR, which is widely used in industrial hydrogen production. These advancements in SAC technology suggest that they could play a pivotal role in scaling up hydrogen production while minimizing costs [36].

While SMRs are efficient and cost-effective, they are not environmentally friendly due to their carbon dioxide emissions. In contrast, electrolysis is a method that utilizes electricity to separate water into hydrogen and oxygen. This method, particularly proton exchange membrane (PEM) electrolysis, offers the production of "green hydrogen" using renewable energy sources. However, electrolysis can be energy-intensive and costly compared to SMR. Biomass gasification presents an alternative approach, converting biomass feedstocks into a syngas through thermal decomposition. This syngas can be utilized to create hydrogen. Biomass gasification provides a sustainable and potentially carbon-neutral approach to generating hydrogen, but its economic feasibility on a large-scale hinges on consistent biomass feedstock availability and effective gasification technologies [32–40]. Various ways of producing hydrogen are evaluated and compared in Table 1.

Table 1. Different methods of hydrogen production [32–40].

Method	Process	Applications
Steam methane reforming	Steam methane reforming is widely used for large-scale hydrogen production in industries. The process includes combining methane with steam at elevated temperatures between 700 and 1000 °C and in the presence of a catalyst to create hydrogen and carbon monoxide [32,33].	SMR is commonly utilized in various sectors like ammonia manufacturing, refining of oil, and producing hydrogen fuel for transportation (Figure 2).
Electrolysis	Electrolysis is a method that employs an electric current to separate water (H_2O) into its constituent parts: hydrogen and oxygen. There are two primary categories: alkaline electrolysis and PEM electrolysis, each of which utilizes distinct electrolytes and operational parameters (Figure 3b).	Electrolysis is an important technology utilized for generating "green hydrogen", which involves employing renewable energy sources such as solar or wind power to power the electrolysis process, thereby avoiding the creation of greenhouse gas emissions [37].
Biomass gasification	Biomass gasification is the process of transforming biomass sources like wood, agricultural leftovers, or organic waste into a syngas (which is a blend of hydrogen, carbon monoxide, and carbon dioxide) by subjecting them to high temperatures for thermal decomposition within a gasifier (Figure 3a).	Biomass gasification can be used to produce hydrogen-rich syngas for various applications, including power generation, heating, and transportation fuel production [40].

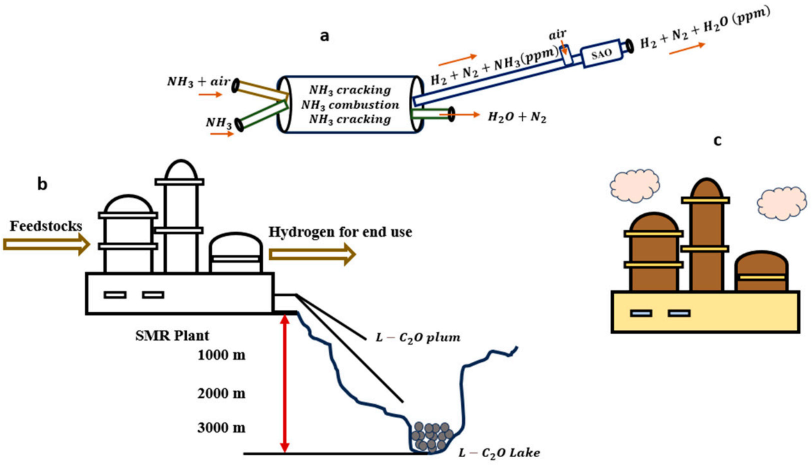

Figure 2. (**a**) Breaking down ammonia into hydrogen through a diagrammatic process. (**b**) The production of hydrogen through the SMR technique and possibilities for capturing and storing carbon dioxide are being explored. (**c**) Oil refining.

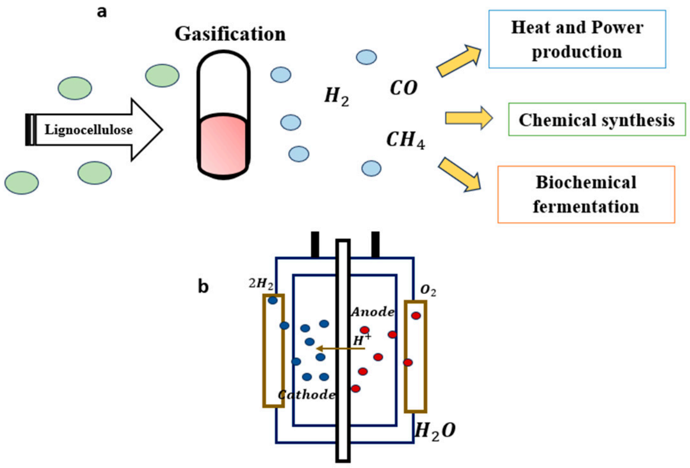

Figure 3. (**a**) Biomass gasification. (**b**) Electrolysis process.

Each of these hydrogen production methods offers distinct advantages and applications, contributing to the diverse and dynamic landscape of hydrogen technologies. As the world transitions towards cleaner and more sustainable energy systems, it is imperative to advance and leverage a variety of hydrogen production methods to reduce carbon emissions across industries, transportation, and power generation [41,42].

A simple visual representation of hydrogen production methods is shown in Figure 4.

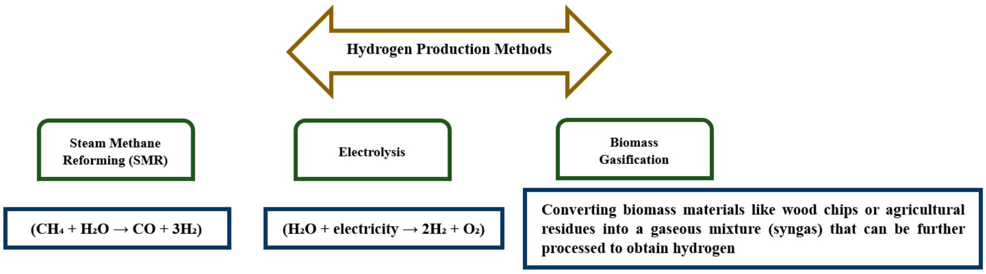

Figure 4. Hydrogen production methods.

In Figure 5:

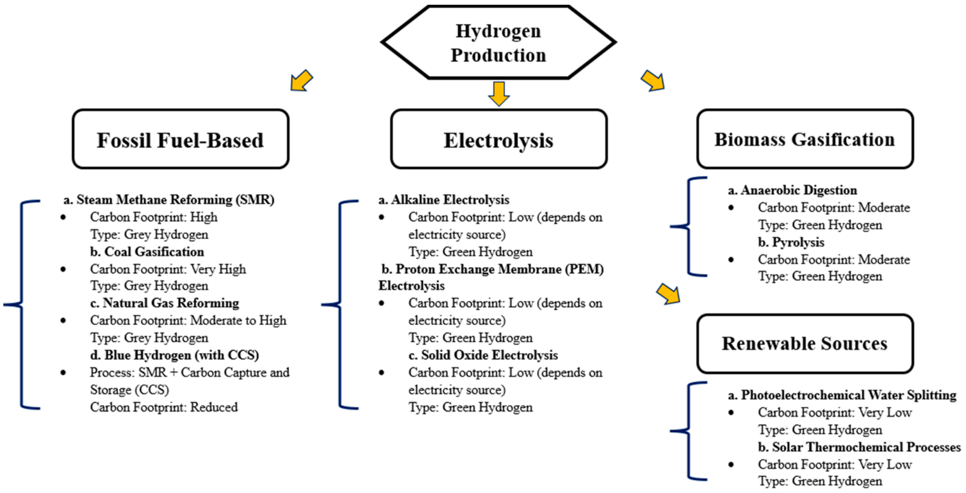

Figure 5. Hydrogen production methods, categorizing them based on their carbon footprints and the type of hydrogen produced.

Fossil Fuel-Based: Methods relying on fossil fuels, generally producing grey hydrogen.

a. SMR: High carbon footprint; produces grey hydrogen.

b. Coal Gasification: Very high carbon footprint; also produces grey hydrogen.
c. Natural Gas Reforming: Moderate to high carbon footprint; yields grey hydrogen.
d. Blue Hydrogen: Incorporates carbon capture and storage, reducing the carbon footprint.

Electrolysis: Uses electricity to produce hydrogen, leading to green hydrogen depending on the energy source.

a. Alkaline Electrolysis: Low carbon footprint; green hydrogen when powered by renewables.
b. PEM Electrolysis: Similar benefits to alkaline electrolysis.
c. Solid Oxide Electrolysis: Also, low carbon footprint when reliant on renewable energy.

Biomass Gasification: Converts organic materials into hydrogen with moderate carbon footprints.

a. Anaerobic Digestion: Moderate carbon footprint; produces green hydrogen from organic waste.
b. Pyrolysis: Moderate carbon footprint; converts biomass to hydrogen.

Renewable Sources: Innovative methods with very low carbon footprints, generating green hydrogen.

a. Photoelectrochemical Water Splitting: Very low carbon footprint; utilizes sunlight directly for hydrogen.
b. Solar Thermochemical Processes: Another very low carbon footprint method using solar energy.

2.2. Discussion of the Environmental Impact

When assessing the environmental impact and carbon footprint of various hydrogen production methods, it is crucial to evaluate the emissions associated with each stage of the process, including feedstock extraction, energy consumption, and waste management [43]. We will now delve into the environmental implications of the three primary hydrogen production methods outlined in Table 2.

In summary, the environmental impact and carbon footprint of hydrogen production methods vary significantly depending on factors such as feedstock sources, energy inputs, and emissions control technologies. It is essential to evaluate the entire hydrogen production lifecycle, from feedstock procurement to the utilization of the final product, to accurately assess the environmental implications of each approach. To minimize the carbon footprint of hydrogen production, transitioning towards renewable energy sources, implementing carbon capture technologies, and adopting sustainable feedstock management practices are crucial. By prioritizing low-carbon and renewable hydrogen production methods, we can mitigate greenhouse gas emissions and accelerate the transition to a more sustainable energy future [44].

Environmental Impacts of Large-Scale Hydrogen Production with CCS

While the integration of CCS technologies with hydrogen production offers significant potential to reduce carbon emissions, several environmental concerns remain. Large-scale hydrogen production, particularly from methods such as SMR combined with CCS, still poses considerable environmental challenges.

1. Energy Intensity of Hydrogen and CCS Processes:

Both hydrogen production and carbon capture are energy-intensive processes. The energy required for separating hydrogen from natural gas or water (in electrolysis) and capturing CO_2 is significant. CCS, in particular, incurs an "energy penalty" of 10–20%, meaning additional energy is needed to capture and compress CO_2, which increases the overall carbon footprint of the production process unless fully powered by renewable energy sources. This higher energy demand can lead to greater consumption of fossil fuels if renewable energy is not used, undermining the environmental benefits [45,46].

2. Risks of CO_2 Leakage:

One of the most pressing concerns associated with CCS is the long-term storage of captured CO_2. Even with rigorous site selection and advanced technologies, there is always a risk of CO_2 leakage from geological storage sites. Leaks could occur through faults or improperly sealed wells, potentially leading to the release of stored CO_2 into the atmosphere, reversing the intended environmental benefits. Moreover, ongoing monitoring and maintenance of storage sites are necessary to ensure safety, which can be both costly and complex [47].

3. Infrastructure and Ecological Impact:

The infrastructure required for large-scale CCS deployment—such as CO_2 transport pipelines, compression stations, and storage sites—can have a direct ecological impact. Building and operating such facilities may disrupt local ecosystems, affect biodiversity, and lead to land-use conflicts. Furthermore, significant water resources are often required for cooling and other processes involved in hydrogen production and CCS, which could strain water supplies, particularly in regions prone to water scarcity [43,48].

4. Long-Term Storage Uncertainty:

The long-term reliability of CO_2 storage is not fully understood. While geological formations like depleted oil and gas reservoirs and saline aquifers are considered safe, ensuring CO_2 remains trapped for centuries or longer remains a challenge. Any future leakage could not only negate the environmental gains but also raise concerns about the safety and efficacy of these storage solutions [49,50].

5. Public Perception and Opposition:

Public opposition to large-scale CCS projects is another challenge. Communities may express concerns about potential CO_2 leaks, environmental degradation, or safety risks associated with the transport and storage of CO_2. Gaining public acceptance and addressing concerns through transparent communication and regulatory measures will be essential for the broader deployment of CCS technologies [51].

6. Land and Water Use Concerns:

CCS projects require large areas for infrastructure, including pipelines and storage sites, which may compete with other land uses such as agriculture or conservation areas. Additionally, CCS operations, especially those linked to hydrogen production from SMR, may require significant water resources, further complicating environmental sustainability in water-stressed regions [44,47,50,52].

In summary, while CCS can significantly reduce CO_2 emissions from hydrogen production, it does not entirely eliminate the environmental footprint. To maximize the benefits of CCS, these challenges must be carefully managed through technological innovations, strong regulatory frameworks, and the integration of renewable energy sources to power hydrogen production.

Table 2. Environmental implications of the three main hydrogen production methods [45–53].

Method	Environmental Impact	Carbon Footprint
Steam methane reforming	SMR is the most commonly utilized approach for generating hydrogen, yet it poses environmental difficulties [45]. It produces CO_2 emissions as a byproduct since it relies on natural gas as a feedstock. For every kilogram of hydrogen produced through SMR, about 9–12 kg of CO_2 are emitted [53].	The carbon footprint of SMR is significant due to greenhouse gas emissions from methane reforming. It contributes to carbon emissions if not coupled with CCS technologies to capture and store the CO_2 byproduct [48].

Table 2. *Cont.*

Method	Environmental Impact	Carbon Footprint
Electrolysis	Using renewable energy sources to power electrolysis can make hydrogen production a more environmentally friendly process [46]. Green hydrogen produced through electrolysis with renewable electricity has minimal environmental impact, as the only byproduct is oxygen. However, if electrolysis is powered by fossil fuels, it can still have a carbon footprint [49].	The carbon footprint of electrolysis depends on the source of electricity used. When powered by renewable energy, electrolysis can be a carbon-neutral or low-carbon method of hydrogen production. However, utilizing electricity from fossil fuels increases the carbon footprint associated with the process [51].
Biomass gasification	Biomass gasification offers a renewable alternative for hydrogen production. While biomass gasification produces carbon dioxide as a byproduct, the carbon released during the gasification process is considered part of the natural carbon cycle when sustainably sourced biomass feedstocks are used [47].	The sustainability of biomass acquisition and the effectiveness of the gasification process are significant factors influencing the carbon footprint of biomass gasification. Biomass gasification has the potential to achieve carbon neutrality or even carbon negativity when the biomass input is sourced sustainably and any carbon emissions are counterbalanced through carbon capture or storage [50,52].

2.3. Risks and Mitigation Strategies for Large-Scale CCS Deployment

The successful implementation of CCS on an industrial scale requires careful consideration of both technical and environmental challenges. Key risks and their corresponding mitigation strategies include [54–56]:

1. CO_2 Leakage: One of the primary concerns with large-scale CCS deployment is the risk of CO_2 leakage from storage sites, which could undermine the environmental benefits of CCS. CO_2 leakage can occur through geological faults or improperly sealed wells. To mitigate this risk, rigorous site selection criteria are crucial. Storage sites should be chosen based on their geological stability and the presence of impermeable cap rocks to prevent CO_2 escape. Additionally, advanced monitoring technologies such as seismic imaging, pressure sensors, and soil gas sampling can detect early signs of leakage, enabling timely intervention.
2. Induced Seismicity: The injection of large volumes of CO_2 into deep geological formations can potentially trigger small seismic events due to increased subsurface pressure. This risk is particularly relevant in regions with existing fault lines or high tectonic activity. Risk assessments should be conducted prior to injection to evaluate the seismic stability of storage sites. Furthermore, pressure management techniques, such as regulating the rate of CO_2 injection, can reduce the risk of induced seismicity. In some cases, water extraction from the formation can help balance the pressure and minimize the likelihood of seismic activity.
3. Public Perception and Acceptance: Public opposition to CCS projects, often due to concerns about safety and environmental impact, can hinder large-scale deployment. Transparent communication about safety measures and environmental benefits is essential for gaining public trust. Engaging with local communities and stakeholders early in the project development process can address concerns and provide accurate information on risks and mitigation strategies. Additionally, government regulations and certification programs can ensure CCS projects comply with the highest safety standards, further building public confidence.
4. Long-Term Liability: The long-term responsibility for stored CO_2 is a significant issue, particularly if leakage occurs decades after injection. To mitigate this risk, long-term monitoring plans should be established for CCS projects, even after injection operations have ceased. Governments should implement clear legal frameworks that define liability for stored CO_2, including who is responsible for monitoring and

remediation in the event of leakage. Insurance mechanisms or carbon storage funds can also be established to cover potential costs associated with future leakage incidents.

5. Ecosystem Disruption: Although the direct environmental footprint of CCS is relatively small, large-scale deployment could disrupt local ecosystems, particularly during the construction of storage sites and pipelines. Environmental impact assessments (EIAs) should be conducted to evaluate and minimize the potential impact on biodiversity and local ecosystems. These assessments should include strategies such as revegetation, habitat restoration, and the use of biodiversity corridors to ensure minimal disruption to wildlife. By incorporating these mitigation strategies into the design and implementation of large-scale CCS projects, we can significantly reduce the potential risks and make CCS a more viable and environmentally sustainable solution for carbon mitigation.

3. Carbon Capture and Storage Techniques

3.1. Explanation of Various CCS Technologies

Post-Combustion Capture: Post-combustion capture is a carbon capture technology that involves capturing CO_2 from the exhaust gases of power plants or industrial facilities after the combustion of fuel. This method typically utilizes chemical solvents or alternative absorbents to trap the CO_2, which can subsequently be compressed and stored underground or repurposed for various applications [54–57].

Pre-Combustion Capture: Pre-combustion capture is a carbon capture method that entails capturing CO_2 before the fuel undergoes combustion. In this process, the fuel is gasified to produce a syngas, which is then processed to separate the CO_2 prior to combustion. This allows for more efficient CO_2 capture due to its higher concentration compared to post-combustion capture [58–60].

Oxy-Fuel Combustion: Oxy-fuel combustion is a carbon capture technology where fuel is burned in an oxygen-rich environment instead of air. This results in a flue gas primarily composed of CO_2 and water vapor, simplifying the process of capturing and separating the CO_2 for storage or utilization. Oxy-fuel combustion can be implemented in power plants or industrial processes to reduce CO_2 emissions [61–64]. Table 3 compares three key factors for various CCS technologies.

Table 3. Comparison of various CCS technologies [55–63].

CCS Technologies	Process	Technology	Applications
Post-combustion capture	Post-combustion capture entails trapping CO_2 from flue gases after the combustion of fossil fuels. This approach is adaptable for integration into current power plants and industrial sites, rendering it a versatile choice for carbon capture [55].	Post-combustion capture technologies commonly utilize solvents or sorbents for absorbing CO_2 from flue gas streams. Once captured, the CO_2 is separated from the absorbent, purified, compressed, and transported for storage [56].	Post-combustion capture is well suited for power plants and industrial facilities that produce high concentrations of CO_2 emissions, providing a viable option for reducing carbon emissions from existing sources [57].
Pre-combustion capture	Pre-combustion capture involves capturing CO_2 before the fuel is burned. This approach is frequently employed in integrated gasification combined cycle (IGCC) power plants and facilities that make use of gasification processes [58].	In pre-combustion capture, the fuel is converted into syngas through gasification, which comprises hydrogen, carbon monoxide, and carbon dioxide. The CO_2 is extracted from the syngas prior to combustion, enabling the capture and storage of CO_2 emissions [59].	Pre-combustion capture is well suited for facilities that utilize gasification processes, such as coal gasification plants or biomass gasification facilities, enabling the capture of CO_2 prior to combustion [60].

Table 3. *Cont.*

CCS Technologies	Process	Technology	Applications
Oxy-fuel combustion	Oxy-fuel combustion includes burning fuel in an oxygen-enriched setting, leading to a flue gas stream primarily comprising CO_2 and water vapor. The water vapor is condensed to generate a nearly pure CO_2 stream that is suitable for capture and storage [61].	Oxy-fuel combustion technologies utilize oxygen rather than air for combustion, streamlining the CO_2 separation process by yielding a concentrated CO_2 stream that is easily captured [62].	Oxy-fuel combustion is commonly used in power generation and industrial applications where high-purity CO_2 capture is desirable, allowing for efficient capture and storage of CO_2 emissions [63].

The integration of CCS technologies with hydrogen production processes necessitates a comprehensive analysis of the efficiency, scalability, and cost implications of each technology. For example, post-combustion capture, a widely used CCS technology, typically achieves a CO_2 capture efficiency of 85–90%. In contrast, pre-combustion capture can reach efficiencies as high as 95%, making it more effective in certain hydrogen production scenarios, particularly gasification-based processes. However, pre-combustion capture often incurs a higher energy penalty, with an estimated efficiency loss of 15–20% compared to post-combustion technologies, which have a lower penalty of around 10–12%. Moreover, the cost of implementing CCS varies significantly depending on the specific technology and the scale of the operation. The cost of post-combustion capture is estimated at USD 40–60 per metric ton of CO_2 captured, while pre-combustion capture can range from USD 50 to 80 per metric ton. Oxy-fuel combustion, although offering high-purity CO_2 streams, presents additional challenges due to the need for an oxygen generation system, leading to increased operational costs. A quantitative analysis of the economic feasibility of integrating CCS into hydrogen production demonstrates that for large-scale projects, such as blue hydrogen production, CCS integration can reduce CO_2 emissions by up to 90% with a marginal increase in the hydrogen production cost of approximately 20–30%. This makes CCS competitive with other decarbonization technologies, provided that appropriate carbon pricing and policy incentives are in place [62–64].

3.2. Importance of CCS in Reducing CO_2 Emissions

CCS is a crucial technology for reducing CO_2 emissions from industrial activities, offering a viable solution to address greenhouse gas emissions and combat climate change [65]. Here is why CCS is essential for industrial decarbonization:

1. Emissions Reduction: Industrial operations contribute significantly to global CO_2 emissions, particularly in sectors such as cement manufacturing, steel production, and chemical processing. By deploying CCS technologies in industrial plants, CO_2 emissions can be captured and securely stored underground, leading to a substantial reduction in the carbon footprint of these industries [66].
2. Process Decarbonization: Many industrial processes rely on fossil fuels for heat and power generation, leading to significant CO_2 emissions. CCS provides a means to decarbonize these operations by capturing CO_2 emissions directly from the source and preventing their release into the atmosphere, assisting industries in transitioning to greener and more sustainable production practices [67].
3. Decarbonization of Energy-Intensive Industries: Industries that rely heavily on energy and have limited low-carbon alternatives, such as cement and steel manufacturing, can greatly benefit from CCS. By capturing and storing CO_2 emissions, these industries can continue their operations while minimizing their environmental impact and meeting emissions reduction targets [68].
4. Technological Innovation: The deployment of CCS technologies in industrial processes drives innovation and research in carbon capture, utilization, and storage. Advancements in capture technologies, storage methods, and process optimization contribute

to the development of more efficient and cost-effective solutions for reducing CO_2 emissions across industries [69].

5. Sectoral Collaboration: CCS encourages collaboration between industry stakeholders, policymakers, and researchers to develop tailored solutions for industrial decarbonization. Partnerships between governments, research institutions, and industry players drive knowledge sharing, investment opportunities, and regulatory support for the effective implementation of CCS in industrial processes [70].
6. Economic Viability: By capturing and monetizing CO_2 emissions through processes like enhanced oil recovery or industrial reuse, CCS can offer economic benefits for industrial facilities. In addition to reducing emissions, CCS can create new revenue streams and support the transition to a low-carbon economy without compromising industrial competitiveness [71].
7. Climate Goals and Sustainability: Meeting climate targets and achieving sustainability objectives requires significant reductions in industrial emissions. CCS provides a proven technology for capturing and storing CO_2 emissions from industrial processes, playing a critical role in achieving net-zero emissions and advancing sustainable industrial practices [72]. Overall, CCS is a vital tool for reducing CO_2 emissions from industrial processes, offering industries a pathway to achieve decarbonization goals, enhance competitiveness, and contribute to global efforts to address climate change. By integrating CCS technologies into industrial operations, industries can lower their carbon footprint, enhance environmental performance, and drive sustainable growth in a carbon-constrained world [73].

4. Integration of CCS into Hydrogen Production

4.1. How CCS Can Be Integrated into Hydrogen Production Processes

Integrating CCS into Hydrogen Production: Incorporating CCS into hydrogen production methods presents a promising approach to mitigating carbon emissions and enhancing the environmental sustainability of hydrogen production [74]. Here is how CCS can be effectively integrated into different hydrogen production methods:

1. SMR with CCS:
    - Integration: In SMR, CO_2 is a byproduct of hydrogen production. Implementing CCS in SMR facilities enables the capture, compression, and underground storage of CO_2 emissions [75].
    - Process: Captured CO_2 from the SMR process undergoes purification and compression before being transported to suitable storage sites for sequestration [76].
    - Environmental Benefits: Combining CCS with SMR significantly reduces CO_2 emissions linked to hydrogen production, promoting environmental sustainability [77].
2. Electrolysis with CCS:
    - Integration: When electrolysis is powered by fossil fuels, it can result in carbon emissions. Integrating CCS with electrolysis facilities allows for the capture and storage of CO_2 emitted during the process [78].
    - Process: CO_2 generated as a byproduct during electrolysis can be captured using CCS technologies and stored underground, effectively reducing the carbon footprint of hydrogen production [79].
    - Advantages: Coupling electrolysis with CCS further lowers emissions and promotes climate-friendly hydrogen generation [80].
3. Biomass Gasification with CCS:
    - Integration: Biomass gasification for hydrogen production can benefit from CCS. CO_2 produced during biomass gasification can be captured and stored, enabling carbon-neutral or even carbon-negative hydrogen production [81].
    - Process: Captured CO_2 from the gasification process undergoes purification and compression before injection into suitable geological storage formations [82].

   - Environmental Benefits: Integrating biomass gasification with CCS enhances the environmental sustainability of hydrogen production, offering a renewable and low-carbon pathway for hydrogen generation [83].

4. Synergy with Renewables:
   - Renewable Energy Integration: CCS can complement renewable hydrogen production methods, such as electrolysis powered by renewable energy sources. Excess renewable energy can be used to capture and store CO_2 emissions from other energy-intensive processes, promoting a circular and sustainable energy system [84].

By integrating CCS into various hydrogen production processes, industries can significantly reduce their carbon emissions, contributing to climate change mitigation efforts and sustainable energy practices. The combination of hydrogen production with CCS not only lowers greenhouse gas emissions but also helps industries transition towards cleaner energy production methods and achieve decarbonization goals [85].

4.2. Synergies, Benefits, and Challenges of Combining CCS with Hydrogen Production

The integration of CCS with hydrogen production presents synergistic opportunities, offering significant benefits but also facing challenges [86]. We will explore these aspects in detail:

Synergies:

1. Emissions Reduction: Integrating CCS with hydrogen production processes enables industries to significantly reduce their carbon footprints by capturing and storing CO_2 emissions, contributing to climate change mitigation efforts [87].
2. Sustainability: The combination of CCS and hydrogen production promotes sustainable energy practices, enhances environmental performance, and supports the transition to low-carbon energy systems [88].
3. Circular Economy: The synergy between CCS and hydrogen production creates a circular energy system where CO_2 emissions are captured and utilized or stored, fostering resource efficiency and environmental stewardship [89].

Benefits:

1. Climate Mitigation: CCS integration into hydrogen production helps industries meet emissions reduction targets, comply with regulations, and support global efforts to combat climate change by reducing CO_2 emissions [90].
2. Cleaner Hydrogen: Incorporating CCS ensures that the hydrogen produced is cleaner and more environmentally friendly, enhancing its marketability and sustainability as a low-carbon energy carrier [91].
3. Decarbonization: The coupling of CCS with hydrogen production accelerates the decarbonization of industrial processes, power generation, and transportation by mitigating emissions and promoting sustainable energy practices [92].

Challenges:

1. Cost: The upfront capital costs of implementing CCS technologies can be substantial, posing a financial barrier to the adoption of CCS in hydrogen production facilities [93].
2. Energy Intensity: CCS integration may increase the energy requirements of hydrogen production processes, affecting overall efficiency and operational costs [94].
3. Infrastructure Requirements: Establishing the infrastructure for CO_2 capture, transport, and storage can be complex and require coordination among stakeholders, regulatory compliance, and investment in storage sites [95].
4. Technological Advancements: The advancement and implementation of CCS technologies for hydrogen production may encounter obstacles concerning technology readiness, scalability, and economic feasibility, necessitating ongoing research and innovation [96].

Conclusion: Despite the challenges, the synergies between CCS and hydrogen production offer a compelling pathway to decarbonize industries, reduce greenhouse gas emissions, and advance sustainable energy solutions. By addressing the challenges through technological advancements, policy support, and collaborative efforts, the integration of CCS with hydrogen production can unlock environmental, economic, and societal benefits [97].

Technological Challenges in Integrating CCS with Hydrogen Production

The integration of CCS into various hydrogen production methods presents several technological challenges, depending on the production method [93–97]:

1. SMR with CCS: SMR is the most widely used method for large-scale hydrogen production, but it generates significant CO_2 emissions. Integrating CCS into SMR facilities involves capturing CO_2 from flue gases, compressing it, and transporting it to storage sites. The main technological challenges include the efficiency of CO_2 capture, the high energy penalty of the capture process (typically 10–15% of the plant's total energy consumption), and ensuring the scalability of capture systems to reduce costs over time. There are also challenges in retrofitting existing SMR plants with CCS technologies.
2. Electrolysis with CCS: When electrolysis is powered by fossil fuels, carbon emissions are still a concern. Integrating CCS with these systems involves capturing the CO_2 generated during electricity production. The challenges here include improving the efficiency of the electrolysis process, particularly with high-temperature electrolysis techniques such as solid oxide electrolysis, which can achieve efficiencies above 85%. However, capturing CO_2 from power plants that use fossil fuels to supply electricity to electrolysis adds complexity, particularly in terms of optimizing both the hydrogen production and carbon capture processes.
3. Biomass Gasification with CCS: Biomass gasification with CCS offers the potential for carbon-neutral or even carbon-negative hydrogen production, but integrating CCS with this method introduces complexities. The CO_2 captured from biomass gasification must be purified and compressed for storage, similar to SMR, but the process of capturing CO_2 from biomass requires advanced purification technologies to handle impurities in the gas stream. Additionally, optimizing the capture process while maintaining the efficiency of hydrogen production is a significant challenge.
4. Infrastructure and Integration Challenges: Regardless of the hydrogen production method, one of the biggest challenges in integrating CCS is developing the necessary infrastructure for CO_2 transport and storage. Pipelines and storage sites must be developed and maintained, which requires substantial investment and coordination between different sectors. The monitoring of long-term CO_2 storage sites to prevent leakage is another significant technological and regulatory hurdle.

5. Opportunities and Advantages

5.1. Opportunities Presented by Integrating CCS into Hydrogen Production

Integrating CCS with hydrogen production presents significant opportunities for achieving carbon neutrality and advancing sustainable energy practices [98]. Key opportunities include:

1. Green Hydrogen Production: Coupling CCS with hydrogen production methods powered by renewable energy sources enables the production of green hydrogen with minimal to no carbon emissions, contributing to carbon neutrality goals [99].
2. Industrial Decarbonization: The integration of CCS into hydrogen production allows industries to decarbonize their operations, reduce greenhouse gas emissions, and transition towards cleaner and more sustainable production methods, aligning with carbon neutrality objectives [100].
3. Sectoral Decarbonization: Integrating CCS into hydrogen production offers a means to decarbonize sectors that are difficult to electrify directly, such as heavy industry, transportation, and power generation, facilitating the transition to low-carbon energy systems [101].

4. Sector Coupling: The synergy between CCS and hydrogen production enables sector coupling, integrating renewable energy sources with carbon capture technologies to produce clean hydrogen for various applications and fostering a holistic approach to achieving carbon neutrality [102].
5. Carbon Offsetting: Capturing and storing CO_2 emissions from hydrogen production processes through CCS provides industries with a carbon offsetting mechanism, helping to balance emissions and achieve net-zero carbon emissions targets [103].
6. Emissions Reduction: Integrating CCS into hydrogen production supports emissions reduction strategies by capturing CO_2 emissions, minimizing the environmental impact of hydrogen production, and contributing to a more sustainable and environmentally conscious energy sector [104].

Path to Carbon Neutrality:

1. Technological Innovation: Continued advancements in CCS technologies, hydrogen production methods, and energy storage solutions drive innovation towards carbon-neutral hydrogen production, offering efficient and scalable pathways to reach carbon neutrality [105].
2. Policy Support: Policy frameworks that incentivize CCS integration into hydrogen production, establish carbon pricing mechanisms, and promote renewable energy adoption create an enabling environment for industries to transition towards carbon neutrality [106].
3. Collaborative Partnerships: Collaborations among governments, industry stakeholders, research institutions, and technology developers foster knowledge sharing, investment opportunities, and regulatory support for implementing CCS in hydrogen production to achieve carbon neutrality [107].
4. Market Transformation: The incorporation of CCS in hydrogen production can disrupt conventional energy systems, accelerate the uptake of low-carbon technologies, and drive market evolution towards a carbon-neutral economy, promoting sustainability and resilience in the energy industry [108].

By leveraging the opportunities presented by integrating CCS into hydrogen production, industries can play a pivotal role in achieving carbon neutrality, reducing greenhouse gas emissions, and fostering a transition towards a more sustainable and environmentally responsible energy landscape [109].

5.2. Possible Advantages in the Areas of Economy, Environment, and Society

The integration of CCS technologies with hydrogen production offers a range of potential economic, environmental, and social benefits, contributing to sustainable energy systems and fostering a transition towards a low-carbon economy [110].

Economic Benefits:

1. Market Growth and Job Creation: CCS integration into hydrogen production can drive the expansion of the clean energy technology market, leading to increased innovation, investment, and job opportunities in the renewable energy and carbon capture industries [111].
2. Revenue Generation: CCS can create new revenue streams through carbon offsetting, emissions trading, and value-added products derived from captured CO_2, boosting economic opportunities for industries [112].
3. Cost Reduction: The scalability and efficiency of CCS technologies in hydrogen production can drive down costs over time, making carbon-neutral hydrogen more competitive and economically viable compared to conventional high-emissions processes [113].

Environmental Benefits:

1. Emissions Reduction: CCS integration into hydrogen production leads to substantial reductions in greenhouse gas emissions, contributing to climate change mitigation efforts by capturing and storing CO_2 emissions [114].

2. Air Quality Improvement: By reducing CO_2 emissions and other pollutants from industrial processes, CCS integration enhances air quality, diminishes health risks associated with pollution, and promotes cleaner environments for communities near industrial facilities [115].
3. Resource Conservation: Shifting towards carbon-neutral hydrogen production through CCS helps conserve natural resources, reduce fossil fuel dependency, and promote sustainable practices that safeguard ecosystems and biodiversity [116].

Social Benefits:

1. Health and Wellbeing: The deployment of CCS technologies in hydrogen production enhances public health by lowering emissions of pollutants and greenhouse gases and creating cleaner and healthier living conditions for communities in industrial areas [117].
2. Community Engagement: Engaging local communities in CCS projects fosters transparency, trust, and social acceptance of sustainable energy initiatives, promoting collaboration and mutual understanding [118].
3. Energy Access and Equity: CCS integration into hydrogen production supports the transition to low-carbon energy systems, promoting equitable access to clean energy, addressing energy poverty, and ensuring energy security for all segments of society [119].

Overall Impact: The economic, environmental, and social benefits of integrating CCS into hydrogen production contribute to the sustainability and resilience of energy systems, helping industries meet climate goals, reduce carbon footprints, and achieve long-term environmental objectives [120]. By embracing CCS technologies in hydrogen production, industries can demonstrate climate leadership, environmental stewardship, and a commitment to transitioning to carbon-neutral energy solutions, setting a positive example for sustainable development and responsible energy practices [121].

The integration of CCS into hydrogen production presents a holistic approach to advancing economic prosperity, environmental stewardship, and social well-being, fostering a transition towards a sustainable, low-carbon future that benefits both current and future generations [122].

6. Challenges and Limitations

6.1. Technical, Economic, and Regulatory Challenges

The integration of CCS technologies with hydrogen production presents several technical, economic, and regulatory challenges that must be addressed for successful implementation as shown in Figure 6. [123].

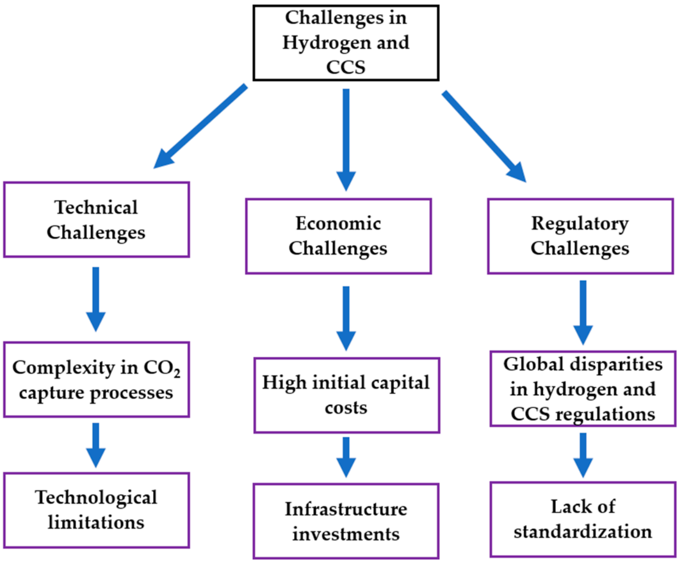

Figure 6. Challenges in hydrogen and CCS integration.

Technical Challenges:

1. Efficiency and Energy Consumption: CCS integration can increase energy requirements and affect overall process efficiency. Innovations in capture technologies, process optimization, and energy management are essential to address these challenges [124].
2. Storage and Transportation: Secure storage of captured CO_2 and efficient transportation to storage sites are crucial technical challenges. Developing safe and cost-effective storage solutions, enhancing transportation systems, and optimizing capture technologies are key focus areas [125].
3. CO_2 Capture Costs: The cost of CO_2 capture technologies can be high, impacting the overall economics of CCS in hydrogen production. Research and development efforts to reduce capture costs, improve efficiency, and scale up technologies are essential [126].

Economic Challenges:

1. Capital Investment: Implementing CCS technologies requires significant upfront capital investment, which can be a barrier to adoption. Financial incentives, supportive policies, and public–private partnerships can help offset initial costs and encourage investment [127].
2. Operating Costs: Operating and maintenance costs associated with CCS integration, including storage, monitoring, and verification, add to the economic challenges. Innovations in operational efficiency, cost-effective solutions, and optimized workflows can help manage ongoing expenses [128].
3. Carbon Pricing and Market Mechanisms: The absence of formal carbon pricing mechanisms or supportive market frameworks can hinder the economic viability of CCS in hydrogen production. Establishing carbon pricing, emissions trading systems, or carbon offset markets can incentivize investment in carbon-neutral technologies [129].

Regulatory Challenges:

1. Regulatory Frameworks: The complexity of regulatory requirements, permits, and approvals for CCS projects presents a regulatory challenge. Streamlining regulatory processes, providing clear guidelines, and promoting regulatory certainty can facilitate the deployment of CCS technologies [130].
2. Liability and Risk Management: Legal aspects related to liability, long-term liability for stored CO_2, and risk management in CCS projects need to be addressed. Establishing liability frameworks, risk mitigation strategies, and insurance mechanisms can provide clarity and confidence for stakeholders [131].
3. Public Acceptance: Social acceptance and stakeholder engagement are vital for the success of CCS projects. Building public awareness, fostering community involvement, and ensuring transparent communication can address concerns and enhance public support for CCS integration in hydrogen production [132].

Strategies for Overcoming Challenges:

1. Research and Development: Continued research and innovation in CCS technologies, storage solutions, and process optimization can drive technical advancements and improve the efficiency and cost-effectiveness of CCS in hydrogen production [133].
2. Collaboration and Partnerships: Collaboration among industry stakeholders, governments, research institutions, and communities is essential to address technical, economic, and regulatory obstacles. Leveraging specialized skills, resources, and information exchange can facilitate the implementation of CCS [134].
3. Policy Support: Implementing supportive policies, incentives, and regulatory frameworks that promote CCS integration into hydrogen production is crucial. Policy alignment with climate goals, carbon pricing mechanisms, and carbon-neutral strategies can create an enabling environment for CCS implementation [135].

Conclusion: By addressing technical, financial, and regulatory challenges through creativity, cooperation, and favorable regulations, the integration of CCS with hydrogen production can overcome obstacles and unleash the full potential of carbon-neutral hydrogen as an eco-friendly energy alternative [135].

6.2. Potential Barriers to Widespread Adoption and Implementation

The widespread adoption and implementation of CCS technologies in hydrogen production require addressing significant technical, economic, regulatory, and social challenges [136].

Technical Challenges:

1. Technology Maturity: CCS technologies are still in the early stages of development or testing, with limited full-scale implementation. Advancements in technology readiness, scalability, and performance are crucial to overcome these technical barriers [137].
2. Energy Intensity: Integrating CCS into hydrogen production processes may increase energy demands and operational complexity, impacting overall efficiency and productivity. Developing solutions to minimize energy requirements and enhance system integration is essential [138].
3. Carbon Capture Efficiency: Achieving high capture rates and optimal CO_2 separation efficiency remains a technical challenge. Enhancing the efficiency, reliability, and affordability of capture technologies is essential for their widespread adoption [139].

Economic Challenges:

1. Capital Investment: The high capital costs associated with CCS deployment, including infrastructure, equipment, maintenance, and operational expenses, can be a significant barrier to adoption. Developing cost-effective solutions, incentivizing investment, and reducing overall lifecycle costs are critical [140].
2. Economic Viability: Industries may face uncertainties regarding the economic viability and return on investment of CCS projects. Clear business cases, financial incentives, and economic assessments are needed to demonstrate the long-term benefits of CCS integration [141].
3. Carbon Pricing: The lack of strong carbon pricing mechanisms or market incentives for CO_2 reduction can hinder the economic viability of CCS projects. Establishing carbon pricing frameworks, emissions trading systems, or carbon offset markets is crucial for overcoming economic barriers [142].

Regulatory and Policy Challenges:

1. Regulatory Complexity: Compliance with evolving regulatory requirements, permitting processes, and environmental standards for CCS projects can be complex and time-consuming. Streamlining regulatory processes, providing clear guidelines, and promoting regulatory certainty can facilitate the deployment of CCS technologies [143].
2. Liability and Risk Management: Legal aspects related to liability, long-term liability for stored CO_2, and risk management in CCS projects need to be addressed. Establishing liability frameworks, risk mitigation strategies, and insurance mechanisms can provide clarity and confidence for stakeholders [144].
3. Policy Alignment: Inconsistencies in national policies, international agreements, and regulatory frameworks related to carbon reduction and CCS deployment can create barriers to widespread adoption. Aligning policies with climate goals, sustainability objectives, and clean energy strategies is essential for promoting CCS implementation [145].

Public Awareness and Social Acceptance:

1. Public Perception: Limited awareness, misconceptions, and concerns about CCS technologies and their environmental impacts can hinder public acceptance. Education, outreach, and stakeholder engagement efforts are necessary to build trust, address misconceptions, and promote social acceptance [146].
2. Community Engagement: Lack of community involvement, consultation, and participation in decision-making processes for CCS projects can lead to resistance and opposition. Establishing transparent communication channels, fostering engagement, and addressing community concerns are key to overcoming social barriers [147].

International Cooperation and Knowledge Sharing:

1. Information Exchange: Limited knowledge sharing, collaboration, and technology transfer among nations, industries, and stakeholders may impede the global deployment of CCS technologies. Promoting international cooperation, fostering best practices, and facilitating technology exchange can enhance adoption and implementation [148].
2. Capacity Building: Insufficient expertise, resources, and institutional capacity for CCS project development and deployment in certain regions can be a barrier to implementation. Building technical capacity, skill development, and knowledge exchange initiatives can support widespread adoption of CCS technologies [149].

By addressing technical, economic, regulatory, and social challenges through innovation, cooperation, policy support, and community involvement, the integration of carbon capture and storage technologies in hydrogen production can overcome obstacles and lay the foundation for a sustainable and environmentally friendly energy future [149].

7. Current Trends and Case Studies

7.1. Review of Recent Developments, Pilot Projects, and Commercial Initiatives

There have been significant advancements in the field of integrating CCS technologies with hydrogen production [150]. Here are some notable examples:

Recent Projects:

- H21 North of England Project: This project aims to transition the UK's gas infrastructure to hydrogen with CCS, reducing carbon emissions from industrial areas and residential heating systems [151].
- H2H Saltend Project: This UK-based project focuses on generating low-carbon hydrogen by capturing and sequestering CO_2 emissions from SMR operations [152].
- Oxyfuel Project at Longannet: This Scottish project is researching oxy-fuel combustion combined with CCS for hydrogen production, aiming to create a concentrated CO_2 stream for storage [153].

Pilot Projects:

- H-Vision Project: This Dutch project seeks to manufacture blue hydrogen by capturing CO_2 from steam methane reforming processes and storing it underground [154].
- Hybrit Initiative: This Swedish pilot project focuses on green hydrogen production and CCS integration, using renewable energy sources to power electrolysis for hydrogen production [155].

Commercial Initiatives:

- Drax Bioenergy CCS Project: Drax Group in the UK is exploring bioenergy with CCS to produce hydrogen, capturing CO_2 emissions from bioenergy production and extracting hydrogen for various applications [156].
- Port of Rotterdam H-vision Project: This project aims to implement large-scale hydrogen production with carbon capture infrastructure at the Port of Rotterdam in The Netherlands [157].

These developments demonstrate the increasing focus on integrating CCS technologies with hydrogen production to decarbonize industrial processes, reduce greenhouse gas emissions, and advance towards a sustainable energy future [158].

Recent Advancements: Recent advancements in hydrogen production and CCS technologies have further demonstrated their viability for large-scale decarbonization. Key examples include:

- Northern Lights Project (2023): This Norwegian project is one of the largest CCS projects in Europe, designed to capture CO_2 from industrial sources and store it in offshore geological formations [159].
- Solid Oxide Electrolysis (2023): Research into SOECs has demonstrated record efficiency levels for green hydrogen production, exceeding 90% when integrated with

waste heat from industrial processes. Pilot projects have successfully scaled up SOEC technology for industrial applications [160].

- Allam Cycle Hydrogen Plant (2022): This plant produces clean hydrogen while capturing CO_2 as part of the production process, utilizing supercritical CO_2 as a working fluid in a closed-loop system. It has successfully demonstrated its capacity to generate 50 MW of clean hydrogen [161].
- Direct Air Capture Integration (2023): Several hydrogen production facilities have begun integrating DAC technology to achieve carbon-negative hydrogen. The Climeworks project in Iceland is a prime example, combining DAC with hydrogen production powered by geothermal energy [162].

Conclusion: These recent case studies and technological advancements illustrate the rapid progress being made in hydrogen production and CCS integration. By leveraging these new developments, the industry is moving closer to large-scale, cost-effective decarbonization.

7.2. Analysis of Successful Case Studies and Lessons Learned

Examining successful case studies of CCS integration into hydrogen production provides valuable insights for future projects. Table 4 highlights key lessons learned from real-world applications.

Table 4. Successful case studies and lessons learned.

Case Studies	Description	Lessons Learned
Norway's Longship Project	The Longship Project in Norway encompasses the Northern Lights CCS project and aims to establish CCS infrastructure for industrial carbon capture and storage, including in hydrogen production processes [160].	The Longship Project underscores the importance of public–private partnerships, regulatory support, and stakeholder engagement in driving large-scale CCS initiatives. It demonstrates the feasibility of integrating CCS into hydrogen production to achieve carbon-neutral goals [161].
Kemper County Energy Facility (U.S.)	The Kemper County Energy Facility in Mississippi combined pre-combustion CCS with gasification technology for power generation, offering insights relevant to hydrogen production [162].	Challenges with project timelines, cost overruns, and technology implementation highlight the need for thorough project planning, scalability assessments, and collaboration among project partners for successful CCS integration [163].
Gorgon Project (Australia)	The Gorgon Project in Australia incorporates CCS to capture and store CO_2 emissions from natural gas processing operations, showcasing industrial-scale CCS integration [164].	Lessons from the Gorgon Project emphasize the importance of addressing geotechnical challenges, monitoring and verification protocols, and public awareness in CCS projects, particularly in hydrogen production applications [165].

Key Lessons Learned from Successful CCS Integration into Hydrogen Production:

Analyzing successful case studies of CCS integration into hydrogen production provides valuable insights for future projects. Key lessons learned include:

1. Early Planning and Risk Assessment: Conducting thorough risk assessments, comprehensive feasibility studies, and scenario planning early in the project lifecycle helps identify potential challenges, mitigate risks, and enhance project preparedness [166].
2. Technology Selection and Scalability: Careful selection of appropriate CCS technologies, evaluation of scalability requirements, and consideration of integration with hydrogen production processes are critical factors for successful deployment and long-term viability [167].
3. Stakeholder Engagement and Communication: Engaging with stakeholders, fostering open communication, and addressing community concerns are essential for gaining support, building trust, and ensuring the social license to operate CCS projects [168].

4. Regulatory Compliance and Permitting: Navigating regulatory landscapes, securing necessary permits, and complying with environmental standards in CCS integration require strategic planning, regulatory expertise, and proactive engagement with regulatory bodies [169].
5. Monitoring and Verification: Implementing robust monitoring, reporting, and verification protocols is vital for ensuring the efficiency, safety, and environmental performance of CCS projects, including in hydrogen production applications [170].
6. Knowledge Sharing and Collaboration: Encouraging knowledge sharing, fostering industry collaboration, and disseminating best practices from successful case studies can drive innovation, accelerate technology deployment, and facilitate the wider adoption of CCS in hydrogen production [171].

By analyzing successful case studies, extracting valuable lessons, and applying best practices, future CCS integration projects in hydrogen production can benefit from practical insights, enhanced project management strategies, and a deeper understanding of key success factors [172].

8. Future Perspectives

8.1. Insights into the Future

The future of CCS integration into hydrogen production holds significant promise as industries, policymakers, and stakeholders prioritize decarbonization, sustainability, and the transition to clean energy systems [173].

Key Trends:

1. Rapid Expansion: The adoption of CCS technologies in hydrogen production is expected to expand rapidly, driven by emissions reduction targets, climate initiatives, and the growing demand for low-carbon hydrogen [174].
2. Technological Advancements: Continued innovations in CCS technologies, efficiency improvements, cost reductions, and scalability enhancements will drive the development of more effective and commercially viable solutions for CCS integration into hydrogen production [175].
3. Renewable Energy Integration: The integration of CCS with electrolysis powered by renewable energy sources is anticipated to grow, leading to increased production of green hydrogen and further decarbonization of industrial processes [176].
4. Industrial Transformation: CCS integration into hydrogen production is crucial for reshaping energy-intensive sectors towards carbon-neutral processes, promoting sustainable industrial practices and improved environmental sustainability [177].

Future Outlook:

1. Infrastructure Expansion: Investments in CCS infrastructure, storage facilities, transportation networks, and hydrogen production plants will expand to support the scaling up of CCS integration into hydrogen production [178].
2. Policy Support: Strong policy frameworks, carbon pricing mechanisms, regulatory incentives, and government support will be instrumental in driving the deployment of CCS technologies and accelerating the adoption of carbon-neutral hydrogen production [179].
3. International Cooperation: Global collaboration, information exchange, partnerships, and technology transfer programs will be vital for driving worldwide efforts towards combining CCS with hydrogen production and meeting carbon-neutrality objectives [180].
4. Innovation and Research: Research and development initiatives, pilot projects, demonstration facilities, and collaborative partnerships will focus on advancing CCS technologies, exploring new applications, and addressing technical challenges to further enhance the feasibility and efficiency of CCS integration into hydrogen production processes [181].

Environmental and Socio-Economic Implications:

- Emissions Reduction: Widespread adoption of CCS integration into hydrogen production will significantly reduce CO_2 emissions, contributing to climate change mitigation, improved air quality, and sustainable development [182].
- Biodiversity Preservation: CCS integration into hydrogen production can help preserve biodiversity and natural ecosystems by promoting sustainable industrial practices, reducing environmental impacts, and fostering responsible resource management [183].
- Job Creation: The growth of CCS integration into hydrogen production will create employment opportunities, promote skill development, and stimulate economic growth in clean energy sectors, contributing to a more resilient and diverse workforce [184].
- Community Engagement: Strengthening community engagement, fostering social acceptance, and ensuring transparent communication with local residents will be essential for building trust, addressing concerns, and promoting the benefits of CCS integration into hydrogen production at the grassroots level [185].

Conclusion: The future of CCS integration into hydrogen production holds great potential for advancing carbon-neutral hydrogen production and achieving a sustainable energy future. By leveraging opportunities, overcoming challenges, and embracing collaborative solutions, the sector is poised for significant growth, technological advancements, and transformative impacts on energy systems, industrial processes, and environmental sustainability [186]. Timeline for advancements in hydrogen technology and carbon capture storage is shown in Figure 7.

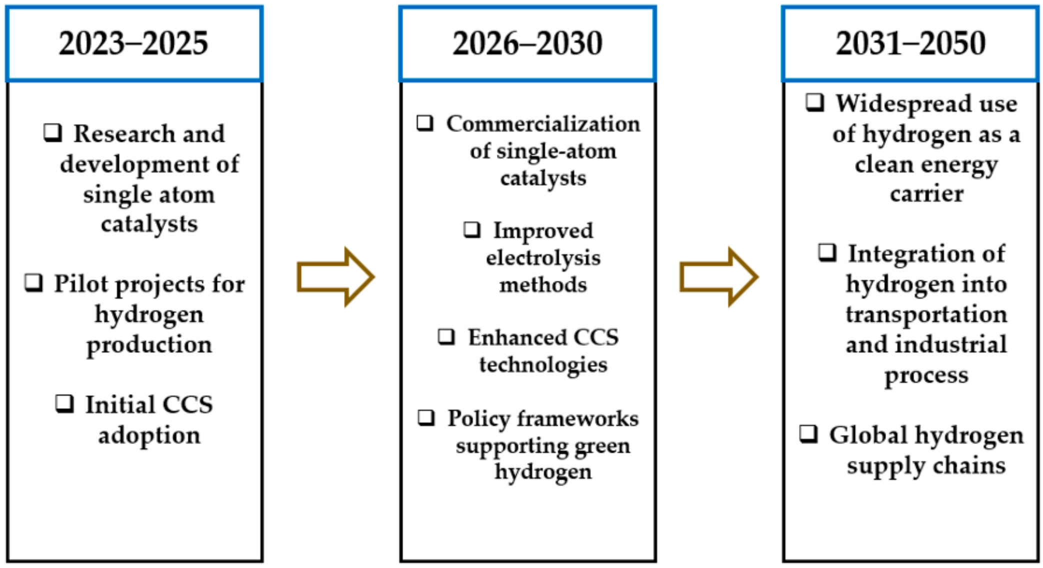

Figure 7. Development of hydrogen technologies.

Consequently, we can conclude [186,187]:

The future of hydrogen production and carbon capture technologies holds immense promise, particularly as innovations continue to emerge in catalyst design, electrolysis efficiency, and large-scale carbon storage. Several key areas of research and development stand out for advancing these technologies:

1. Catalyst Technologies: Breakthroughs in single-atom catalysts and other novel materials have the potential to significantly reduce the energy consumption of hydrogen production through electrolysis. Future research should focus on improving the efficiency and scalability of these materials to make green hydrogen production more cost-competitive.
2. Renewable Energy Integration: A key future perspective is the integration of hydrogen production with intermittent renewable energy sources like wind and solar. Research

should aim to develop flexible, efficient systems that can store excess energy as hydrogen, enhancing grid stability and energy storage solutions.

3. Policy and Economic Incentives: Supportive policy frameworks that incentivize investment in green hydrogen and carbon capture, as well as international collaborations to standardize regulations, are crucial for shaping the future of these technologies.
4. Scalability and Infrastructure: While pilot projects have demonstrated feasibility, large-scale deployment of hydrogen production and CCS infrastructure remains a challenge. Future work should explore solutions for scaling up these technologies, particularly in regions with abundant renewable resources and industrial demand.

8.2. Discussion of Emerging Technologies, Research Directions, and Policy Considerations

- Emerging Technologies:
    1. Advanced Capture Methods: Continued research focuses on enhancing capture technologies to improve efficiency, reduce energy requirements, and lower costs. Innovations in solvent-based capture, membrane technologies, and solid sorbents aim to optimize CO_2 capture in hydrogen production processes [187].
    2. Direct air capture technologies are increasingly recognized for extracting CO_2 directly from the air. By incorporating DAC with hydrogen production, carbon-negative hydrogen pathways can be realized, providing a flexible strategy to achieve net-negative emissions [188].
    3. Novel Electrolysis Techniques: Studies are investigating improvements in electrolysis techniques, including high-temperature electrolysis, solid oxide electrolysis cells, and membrane electrolysis, to enhance efficacy, lower energy usage, and facilitate extensive green hydrogen manufacturing [189].
    4. Storage Optimization: Innovations in CO_2 storage methods, including geological sequestration, mineralization, and utilization, aim to enhance CO_2 storage capacities, improve containment effectiveness, and ensure long-term stability for carbon sequestration in hydrogen production applications [190].

Consequently, we can conclude that [187–190]:

Emerging technologies in hydrogen production and carbon capture are crucial to achieving sustainable, large-scale decarbonization. Two key areas that hold significant promise for future development are DAC and novel electrolysis techniques.

1. Direct air capture is a groundbreaking technology that directly removes CO_2 from the atmosphere, offering the potential for large-scale carbon removal. DAC systems typically rely on chemical processes using solid sorbents or liquid solvents to capture CO_2 from ambient air, which is then either sequestered underground or utilized in synthetic fuel production. Recent advancements have led to improved efficiency and cost reductions, though the current cost is estimated to be between USD 100 and USD 300 per metric ton of CO_2 captured. However, with ongoing research and increased deployment, costs are expected to decrease significantly. DAC offers a unique opportunity for producing carbon-neutral or carbon-negative hydrogen when integrated with hydrogen production systems. Captured CO_2 can be combined with green hydrogen to create synthetic fuels, or it can be stored permanently, offsetting emissions from other sectors.
2. Recent advancements in water electrolysis have focused on improving efficiency and reducing costs. High-temperature electrolysis (HTE), using solid oxide electrolysis cells (SOECs), has emerged as a promising method for producing green hydrogen. SOECs operate at temperatures between 600 °C and 800 °C, utilizing heat energy to lower the electrical energy required for splitting water into hydrogen and oxygen. This results in overall system efficiencies of above 85%, which is significantly higher than conventional PEM or alkaline electrolyzers, which typically operate at 60–70% efficiency.

Another promising development is membrane-free electrolysis, which eliminates the need for costly membranes by using advanced materials for catalyst separation. Furthermore, novel single-atom catalysts and perovskite-based catalysts have shown significant potential to enhance the electrolysis process by lowering the activation energy required, further improving the efficiency of hydrogen production.

These emerging technologies represent the next frontier in both carbon capture and hydrogen production. Direct air capture holds the potential to remove vast amounts of CO_2 from the atmosphere, while high-temperature and novel electrolysis techniques offer more efficient methods of producing green hydrogen. Continued research and innovation in these areas will be critical for reducing costs and scaling up these technologies for widespread adoption.

- Research Directions:
    1. Carbon Recycling: Research is looking into carbon recycling approaches where captured CO_2 is transformed into valuable products like synthetic fuels, chemicals, or construction materials, establishing a circular carbon economy and boosting the economic feasibility of hydrogen production with CCS [191].
    2. Hybrid Energy Systems: Combining renewable energy sources with CCS-integrated hydrogen production can lead to the development of hybrid energy systems that leverage intermittent renewables alongside carbon capture technologies for sustainable and resilient energy generation [192].
    3. Material Innovation: Research on advanced materials, catalysts, and membranes for CO_2 capture, electrolysis, and storage aims to enhance the performance, durability, and efficiency of hydrogen production processes, driving technological breakthroughs in clean hydrogen production pathways [193].
    4. System Integration: Comprehensive studies on system integration of CCS technologies with hydrogen production facilities focus on optimizing process flows, improving energy utilization, and minimizing environmental impacts to create integrated, efficient, and sustainable hydrogen production systems [194].

To provide a more comprehensive understanding of the economic viability of CCS integration in hydrogen production, it is essential to conduct a techno-economic assessment (TEA) that considers the capital and operational costs, as well as the potential benefits and challenges [195–199].

1. Capital Costs:

The capital expenditure (CAPEX) for integrating CCS into hydrogen production is primarily driven by the construction of capture facilities, CO_2 transportation infrastructure, and long-term storage sites. For example, the cost of post-combustion CCS systems is estimated to be USD 40–60 per metric ton of CO_2 captured, while pre-combustion systems can range from USD 50 to 80 per metric ton. These costs vary based on the size of the hydrogen production plant and the type of CCS technology used. In blue hydrogen projects (hydrogen from natural gas with CCS), the CAPEX is expected to increase by 20–30% due to the additional costs of installing and maintaining CCS equipment.

2. Operational Costs and Energy Penalty:

In addition to capital costs, the operational expenditure (OPEX) for CCS includes the energy required to capture, compress, and transport CO_2. This "energy penalty" is typically 10–20% of the plant's total energy consumption, depending on the technology. For example, pre-combustion capture has a higher energy penalty than post-combustion capture due to the need for gasification processes. These increased energy costs must be factored into the overall economic model, as they can reduce the efficiency of hydrogen production.

3. Potential Revenue and Cost Savings:

While CCS integration adds upfront costs, it can also create revenue streams and cost-saving opportunities. For example, CO_2 captured via CCS can be sold for EOR, which could generate revenue of USD 20–30 per metric ton of CO_2 in certain markets. Additionally, industries that implement CCS can benefit from carbon credits or avoid penalties under carbon pricing mechanisms, which could result in savings of USD 50–100 per metric ton of CO_2, depending on regional carbon pricing policies.

4. Levelized Cost of Hydrogen (LCOH):

A rigorous techno-economic analysis would also assess the levelized cost of hydrogen (LCOH), which includes the CAPEX and OPEX over the plant's lifetime. Studies have shown that the LCOH for hydrogen production with CCS typically ranges from USD 1.50 to USD 3 per kg of hydrogen, compared to USD 0.80 to USD 2 per kg for conventional hydrogen production without CCS. This indicates that CCS can increase the cost of hydrogen production by 20–40%, but this cost could be offset by revenue from carbon credits or the sale of CO_2 for EOR.

5. Cost–Benefit Analysis (CBA):

When conducting a cost–benefit analysis, it is important to consider the long-term benefits of reducing CO_2 emissions and the potential economic gains from government incentives. For example, many countries provide financial support for green hydrogen projects, including tax credits, grants, or subsidies. These can reduce the overall costs and improve the return on investment (ROI). A comprehensive CBA would also factor in the environmental and societal benefits of reducing emissions, which are increasingly important in policy-driven markets.

- Policy Considerations:
    1. Carbon Pricing Mechanisms: The implementation of robust carbon pricing mechanisms, emissions trading systems, and carbon markets can incentivize investments in CCS-integrated hydrogen production, drive decarbonization efforts, and align economic incentives with climate goals [200–205].
    2. Regulatory Frameworks: Developing clear regulatory frameworks, permitting processes, and standards for CCS technologies in hydrogen production is essential for providing regulatory certainty, ensuring compliance, and fostering a conducive environment for CCS deployment [206,207].
    3. Innovation Support: Policy initiatives that promote research funding, innovation incentives, technology demonstration programs, and collaborative partnerships can accelerate the development and deployment of emerging technologies for clean hydrogen production with CCS [208,209].
    4. International Cooperation: Global cooperation, sharing of knowledge, and standardization among nations can ease the transfer of expertise, optimal methods, and technological advancements, promoting the uptake of CCS-incorporated hydrogen production worldwide [210,211].
- Future Landscape:

The future landscape of clean hydrogen production with CCS is poised for transformation through technological advancements, research breakthroughs, and policy initiatives that prioritize decarbonization, sustainability, and climate resilience. By embracing innovative solutions, fostering collaboration, and driving policy support, the clean hydrogen sector is set to play a pivotal role in achieving a low-carbon energy future [212,213].

Policy Recommendations for Promoting CCS-Integrated Hydrogen Production

1. Carbon Pricing Mechanisms:

Establish robust carbon pricing systems such as carbon taxes or emissions trading schemes. These mechanisms will incentivize the adoption of CCS by making carbon emissions costly and encouraging investment in cleaner technologies like CCS-integrated hydrogen production [189,191].

2. Regulatory Frameworks and Standards:

   Develop clear and streamlined regulatory processes for CCS deployment, including permitting, monitoring, and long-term storage. Providing regulatory certainty will help industries adopt CCS while ensuring environmental and safety standards [187,195].

3. Financial Incentives and Subsidies:

   Governments should offer financial incentives, such as tax credits, grants, or subsidies, to offset the high initial costs of CCS technologies. This support will lower the financial barriers and encourage companies to invest in CCS-enabled hydrogen production [192,201].

4. Research and Innovation Funding:

   Invest in research and development for CCS technologies to improve efficiency, reduce costs, and scale up deployment. Funding pilot projects and supporting innovations such as advanced capture technologies and novel storage solutions will accelerate CCS adoption [202,210].

5. International Cooperation:

   Foster global collaboration through information sharing, technology transfer, and harmonized regulatory standards. This will streamline CCS implementation across borders, allowing for large-scale deployment and cost reductions through shared best practices [205,212].

6. Public Awareness and Engagement:

   Implement strategies to increase public awareness and acceptance of CCS projects by promoting transparent communication, community involvement, and education on the environmental benefits of CCS and hydrogen production [186,213].

8.3. Techno-Economic Analysis of Hydrogen Production with CCS

Techno-economic analysis of different hydrogen production pathways, including steam SMR, electrolysis, and biomass gasification, with and without CCS, is mentioned in Table 5. The table compares the levelized cost of hydrogen (LCOH), CO_2 capture efficiency, CO_2 capture cost, and energy penalty for grey, blue, and green hydrogen production methods. The analysis highlights the cost and environmental trade-offs associated with integrating CCS into hydrogen production processes.

Table 5. Techno-economic analysis of hydrogen production with CCS [195–222].

Hydrogen Production Method	Hydrogen Type	LCOH (USD/kg H_2)	CO_2 Capture Efficiency (%)	CO_2 Capture Cost (USD/Metric Ton CO_2)	Energy Penalty	References
SMR	Grey hydrogen	USD 0.80–2	No CO_2 capture	Not captured (high emissions)	No energy penalty (without CCS)	[195,214]
SMR + CCS	Blue hydrogen	USD 1.50–3	85–95%	USD 40–60	10–15% due to CCS	[196,215]
Electrolysis (renewable energy)	Green hydrogen	USD 2.50–6	Zero emissions (no CO_2 to capture)	No CO_2 capture	No energy penalty (No CCS)	[197,216]
Biomass gasification + CCS	Blue hydrogen	USD 1.80–3.50	90–95%	USD 50–80	12–18% due to CCS	[197,198]
Solid oxide electrolysis (SOEC)	Green hydrogen	USD 2–4.50	Zero emissions (no CO_2 to capture)	No CO_2 capture	8–12% efficiency loss (energy efficient)	[217–222]

Description: LCOH (USD/kg H_2): The levelized cost of hydrogen, which includes both capital and operating costs over the lifetime of the plant. CO_2 Capture Efficiency: For green hydrogen, which does not involve CO_2 emissions (since it uses renewable electricity for electrolysis), I replaced "N/A" with "zero emissions (no CO_2 to capture)." CO_2 Capture Cost: For green hydrogen, there are no costs associated with CO_2 capture since there are no emissions to capture. I replaced "N/A" with "no CO_2 capture." Energy Penalty: For grey hydrogen and green hydrogen, there is no CCS involved, so I explained that "no energy penalty" applies, meaning there is no efficiency loss due to CO_2 capture.

9. Conclusions

The integration of CCS technologies with hydrogen production is essential for achieving carbon-neutral energy systems. While significant technical, economic, and regulatory challenges exist, ongoing research, innovation, and policy support are crucial for overcoming these barriers. Successful integration can drastically reduce emissions, facilitating the transition of industries towards sustainable practices. This integration will play a pivotal role in the global effort to combat climate change and promote cleaner energy solutions.

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