

An Assessment of Advanced Sorbents for Efficient CO₂ Capture in Blue Hydrogen Plants

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ABSTRACT

Developments in carbon dioxide (CO₂) capture technologies for blue hydrogen generation have identified the potential for advanced sorbents, especially solid sorbents and hybrid absorption-adsorption technologies, to deliver high efficiencies and low environmental costs in CO₂ capture. Yet, current research is often disconnected, addressing only individual dimensions such as techno-economic, environmental, or technical performance, thus making it difficult to compare and make decisions. This research aims to bridge this gap by proposing a multi-criteria evaluation framework for advanced sorbents for effective CO₂ capture in blue hydrogen production. Our framework incorporates multiple assessment criteria, such as technical performance, economic viability, environmental sustainability, scalability and innovation. It employs a hybrid evaluation method with a combination of Techno-Economic Assessment (TEA), Life Cycle Assessment (LCA) and performance-based assessment for a comprehensive assessment of sorbent technologies. Related studies have shown that solid sorbent technologies can have more than 90% CO₂ removal efficiency and greater than 95% purity with reduced costs compared to traditional amine-based technologies, while hybrid systems exhibit better long-term economic viability and improved capture performance. Visual tool (heatmap) and percentage analysis were used to present interpretability and aid decision-making. The new framework has better integration, standardization and industrial practicality than the existing frameworks. The research contributes to knowledge by offering a consistent and scalable evaluation framework that improves the design and selection of advanced sorbents, which in turn aids in the design of cost-effective and sustainable CO₂ capture technologies for blue hydrogen plants and worldwide decarbonisation.

Keywords: Life Cycle Assessment, Techno-Economic Assessment, Sorbents, CO₂ Capture, Blue Hydrogen Plants.

INTRODUCTION

Recent researches on CO₂ capture for blue hydrogen production suggest that emerging sorbent technologies, including solid sorbents and hybrid absorption-adsorption systems, offer high CO₂ capture efficiency (>90%) and purity (>95%) along with low energy losses and costs. These studies also indicate that hybrid systems offer better long-term cost-effectiveness, while adsorption systems have lower emissions and payback periods. New technologies like membrane and advanced adsorbents have also shown promise in reducing the environmental impact of traditional amine-based systems, which are energy and cost-intensive. Yet, despite these developments, there is a significant gap in the literature due to the lack of a harmonized framework to assess advanced sorbents. The majority of studies employed stand-alone evaluation methods, either in terms of technical, economic or environmental analysis. As a result, comparisons are inconsistent, and there is a lack of standardized evaluation criteria and guidance on the optimal technology for large-scale applications. Moreover, existing frameworks lack decision-making support, scalability and visual analytics,

which restrict their utility in industrial and political settings. To overcome these issues, this research seeks to propose a structured multi-criteria assessment framework for innovative sorbents in CO₂ capture for blue hydrogen plants. This framework considers technical, economic, environmental, scalability and innovation aspects in a systematic manner. It uses a mixed assessment approach that incorporates

Techno-Economic Assessment (TEA), Life Cycle Assessment (LCA) and performance metrics to provide a more comprehensive and consistent scoring system. The proposed framework is far more effective than other previously analyzed frameworks in several ways. First, it overcomes fragmentation by bringing together various evaluation aspects into a cohesive framework, allowing comparison of various sorbent technologies. Second, it includes multi-criteria decision analysis (MCDA), which improves decision-making by weighing up the trade-offs between cost, efficiency and environmental impact. Third, it uses visual evaluation heat map tools and percentage-based analyses, which enhance its clarity, interpretability and stakeholder friendliness. Fourth, the framework is scalable and applicable to industrial practice, aspects that are often neglected in current models. Finally, it is consistent with the principles of standardized assessment, overcoming inconsistencies in previous techno-economic and life cycle assessments. The research contributes to knowledge in developing a next-generation evaluation framework that not only brings together the results of current research, but extends them by offering an integrated, transparent and decision-focused framework. The framework facilitates the selection and optimization of efficient, economical and scalable CO₂ capture technologies, by enhancing the accuracy, consistency and usefulness of sorbent assessment, thus advancing sustainable blue hydrogen production and global decarbonisation.

Related Works

CO₂ Capture in Blue Hydrogen Plants

Blue hydrogen is made by the high temperature steam oxidation of fossil methane. The carbon dioxide (CO₂) formed is partially captured, stored and partially released [1]. Proposals for blue hydrogen projects are surfacing in Europe and North America, mostly based on ATR process, with the target of capturing more than 95 % of the carbon dioxide formed. "Blue" hydrogen, produced from natural gas with CO₂ capture and storage (CCS), can help to build up a low carbon hydrogen market, which in turn contributes to decarbonize industry and difficult-to-electrify transport. In order to deliver a low carbon blue hydrogen, high CO₂ capture rate and very low methane loss along the natural gas supply chain are critical [2]. The study also highlights that the residual direct CO₂ emissions from blue H₂ plants are linked to the following three factors: (i) unconverted CH₄ from reformer, (ii) unconverted CO from the water gas shift (WGS) section and (iii) uncaptured CO₂ from the CO₂ separation unit. The study suggests that to increase the CO₂ capture rate, the following options are possible:

1. To enhance CH₄ conversion in the reformer, increasing reformer exit temperature. This is a problem in FTR, where the reformer exit temperature is constrained by the stress resistance of the reactor material and, consequently, methane slip is much greater than in ATR. The possibility of very high reforming temperatures is supported by the electrified section, which heats up the reacting syngas via electric heating from the inside of the reactor, without warming up the pressure-resistant reactor shell.
2. To enhance CO conversion in the WGS section, by lowering the LT-WGS outlet temperature. This can be done using a cooled reactor or two or more intercooled LT-WGS reactors.
3. To develop the process for the removal of CO₂ from syngas for very high CO₂ separation efficiencies (>99 %). This high separation efficiency and high hydrogen recovery (>99.9 %) can be obtained by suitable process design (two-stage absorption with semi-lean and lean solvent and recirculation of high-pressure flash gas to the absorber) and is standard practice for decades for ammonia plants.

The aim of this study was to assess the potential of new, "Powdrogen" polygeneration plants to simultaneously produce low carbon hydrogen and dispatchable low carbon electricity, with economic benefits versus separate generation of power and hydrogen with CCS and storage. The study shows the

Powdrogen concept is based on integrating a chemical island (FTR or ATR) with a hydrogen-fired gas turbine combined cycle (GTCC) to selectively produce blue hydrogen and/or power.

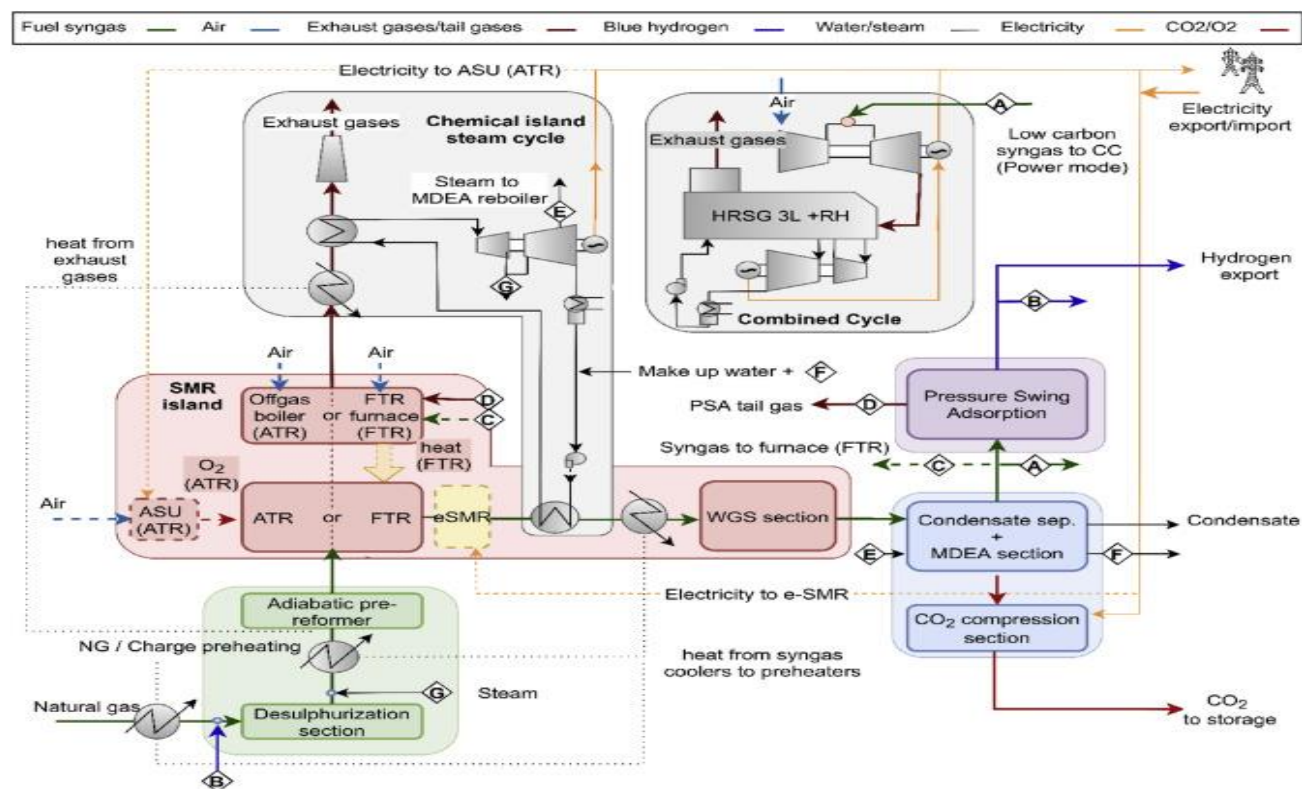


Fig. 1: Block diagram of the “Powdrogen” plants [2]

[3] analysed several blue hydrogen production facilities, including: (i) Fired Tubular Reforming-based process (also known as SMR in the report) with post-combustion capture, (ii) Auto Thermal Reformer (ATR) with Gas heated reformer (also known as Low Carbon Hydrogen - LCH), (iii) Electrified Steam Methane Reformer (ESMR), and (iv) Partial Oxidation (POX). The four plants feature CO₂ capture rates of 90 %, 93.6 %, 98.6 % and ~88 %2, respectively. Green hydrogen has a high decarbonisation potential and is the resource most in line with carbon inactiveness scheme. The biggest challenge in any hydrogen project regardless of colour is the economics. Hydrogen is corrosive and highly combustible therefore converting the oil and gas infrastructure to be safe for hydrogen is expensive [4]. The United Nations Sustainable Development Goals (UNSDGs) is forcing the world into a fast-tracked approach to the sustainability agenda and decarbonisation. To meet these goals, Green hydrogen (GH) is the key for Africa with its high renewable energy potential to make economic gains and provide employment opportunities to its fast-growing population through GH production. The production and export of GH for Africa has the potential for tremendous economic and social benefits. Research into GH utilisation is getting popular among researchers as it is a clean energy source and a potential alternative to fossil fuels [5]. The search for clean, environmentally friendly and sustainable energy sources has also boosted researchers' interest in GH production [6]. The majority of systems used globally are related to energy. As a result, energy is now produced from various renewable sources such as solar and wind. The fact is, it has been generated mostly from fossil fuels, which has changed our climate through the years, from damaging our ozone layer and humans due to the over-formation of Carbon (CO₂). Many nations have announced net-zero emissions targets as a commitment to start to reduce ozone-harming substance emissions as the urgency to combat climate change and limit global warming increases.

Advanced Sorbents for CO₂ Capture In Blue Hydrogen Plants

A recent study by [7], investigated five key pathways for carbon capture: advanced solvent-based capture, solid sorbent technologies, membrane-based separation, cryogenic carbon capture (CCC), and oxy-fuel combustion integration. The study compared the technologies in terms of their technical

potential, economic viability, and long-term sustainability. The study defines Solid Sorbent Technology (SST) as a new approach that employs a solid adsorbent in a continuous Temperature Swing Adsorption (TSA) fluidized bed process to extract CO₂ from flue gas. Compared to the state-of-the-art liquid amines technology, the process simultaneously offers > 90% capture efficiency and > 95% purity of CO₂ with negligible to no process emissions and at reduced costs. As such, [8] provides a techno-economic analysis (TEA) of four different solid sorbent technologies as an alternative to the conventional amine scrubbing method for post-combustion CO₂ capture with internal heat integration. [9] proposed a natural gas combined cycle (NGCC) power station with a hybrid CCS system that can maintain high CO₂ capture rates and seamlessly switch between high and low loads to meet these objectives.

Recent research by [10][11] compares key CCS technologies such as pre-combustion capture, post-combustion capture (e.g., amine scrubbing), absorption, adsorption and membrane separation. This study compares these technologies for their efficiency in CO₂ capture, cost (capital and operational costs), and environmental impacts (such as energy use, water consumption and waste production). The findings show that although post-combustion capture with amine scrubbing is well-developed and highly efficient in capturing CO₂, it has high energy penalties and environmental costs. Pre-combustion capture is more efficient and with reduced energy penalties, but it is more expensive and faces scalability issues. Novel technologies such as adsorption and membrane separation can be efficient and have low environmental impacts but need to be developed to enhance their cost-effective performance. The research suggests the best option of CCS technology for blue hydrogen production is dependent on a combination of variables such as plant scale, natural gas characteristics, CO₂ sink, and cost. A holistic evaluation framework is needed to guide decision-making in the choice of the most suitable technology in terms of efficiency, cost and environmental impacts. This study aids decision making to achieve sustainable and economical blue hydrogen production.

Blue hydrogen can play a vital role in addressing global warming. Therefore, enhancing the carbon capture process in blue H₂ plant designs is essential. This paper compares the feasibility of technologies for 100 and 400 tonnes-per-day plants, in terms of technical, environmental and economic performance using a process simulator (Aspen HYSYS) and life cycle assessment (ReCiPe) methods. The absorption/adsorption hybrid system was found to have better long-term profitability and greater net present value (NPV), despite having a higher capital cost. The all-adsorption system, on the other hand, had a lower payback period, and lower equivalent emissions. The cost of hydrogen production was \$2.20/kg for the former and \$1.80/kg for the latter, and there was a marginal difference in rate of return. Moreover, the sensitivity study showed the effects of the cost of natural gas, sales price of H₂ and CO₂ and cost of zeolite on the profitability. Finally, scale-up demonstrated a larger plant to be more profitable [12]. Figures 2 and 3 shows the impact of using amine separation and solid adsorption in blue hydrogen plants by the study.

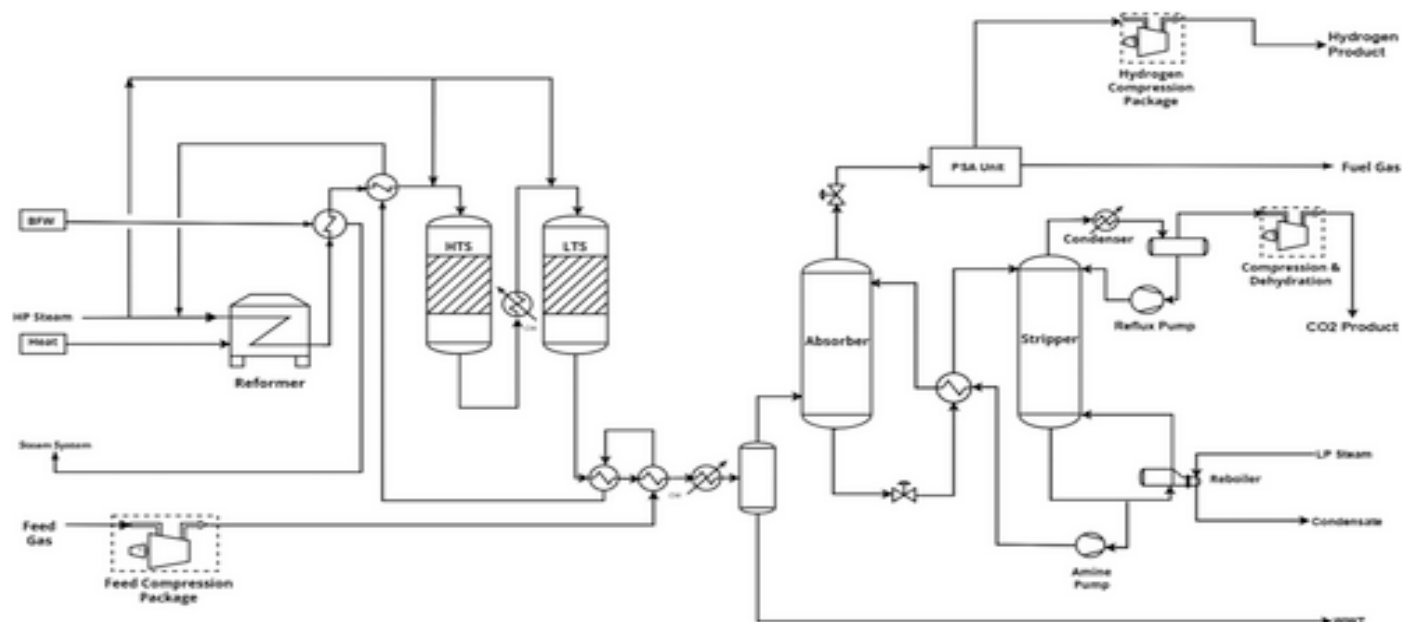


Fig. 2: Process flow diagram of blue H₂ plant with hybrid absorption/adsorption CO₂ capture unit. [12a]

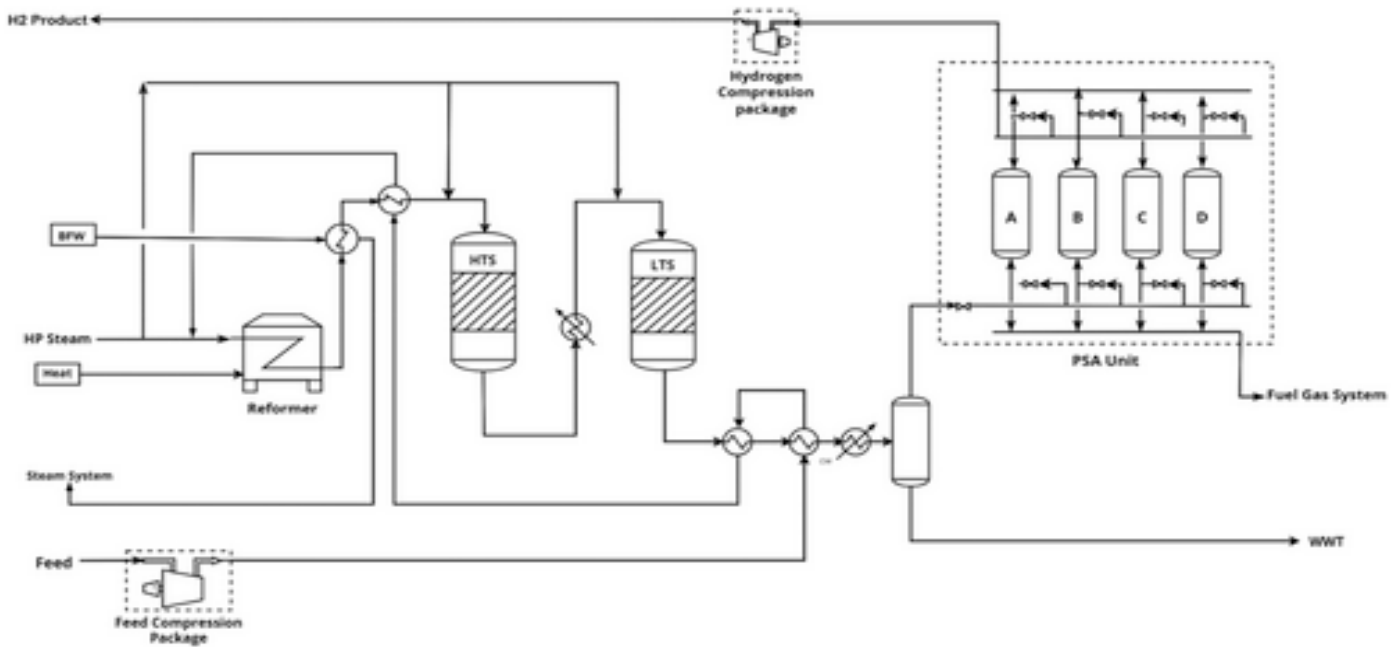


Fig.3: Process flow diagram of blue H₂ plant with fully adsorption CO₂ capture unit. [12b]

In another study, [13] note that blue hydrogen production, generally accomplished through a combination of steam methane reforming and amine-based CO₂ capture, is considered a cost-effective pathway to clean hydrogen. But it is energy intensive due to the solvent regeneration process. The authors suggested a hybrid process that combines steam methane reforming with membrane CO₂ capture and O₂-enriched combustion (figure 4) to address this issue. They used process simulations to perform techno-economic and environmental assessments considering key parameters on the levelled cost of hydrogen (LCOH) and CO₂ emissions. The best results were achieved with 30% oxygen enrichment, vacuum pumping and CO₂ capture by feed compression at 11 bar. It resulted in an LCOH of ~\$1.8/kg H₂ and total specific CO₂ emissions of ~4.9 kg CO₂/kg H₂.

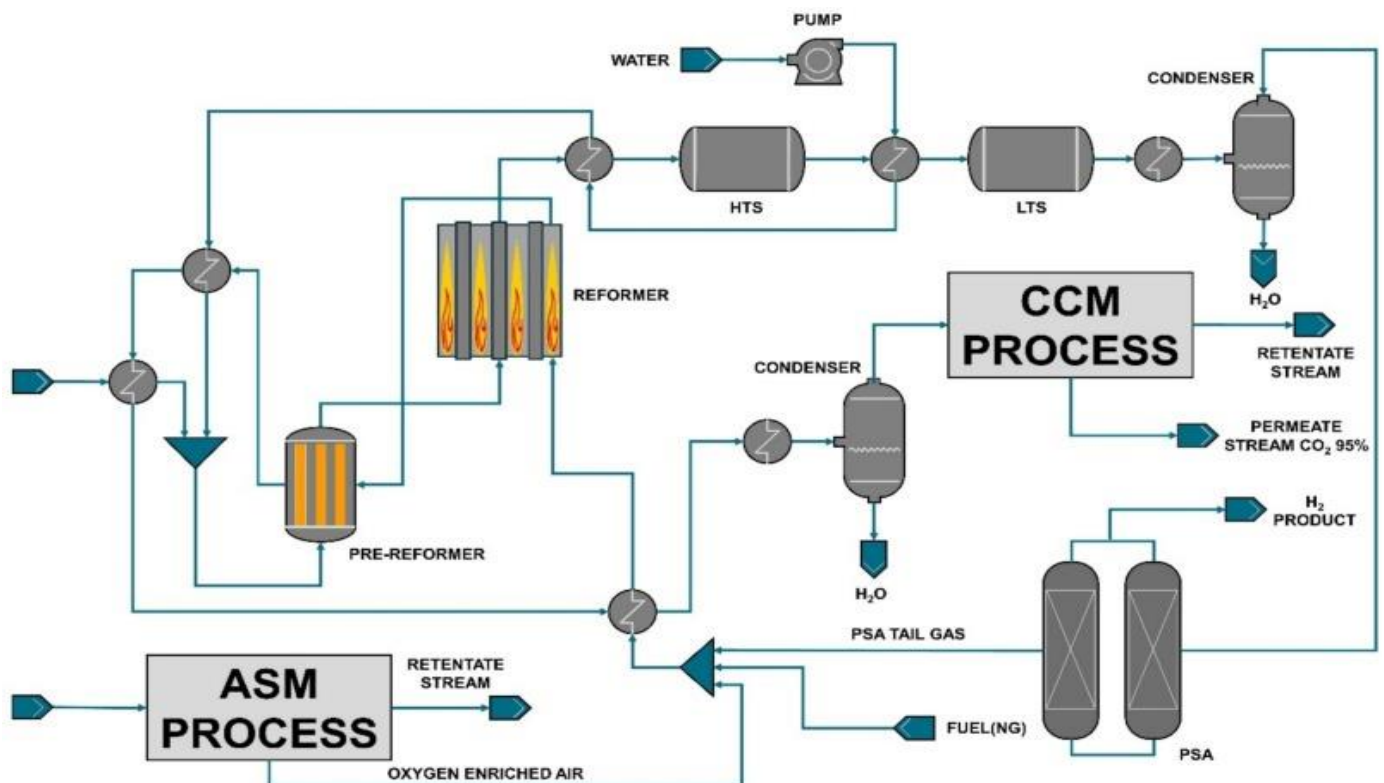


Fig. 4: flowsheet of the hybrid process [13]

A companion paper by [14] also mentioned that blue hydrogen (from fossil fuels with CO₂ removal) is presently considered as the interim solution between the high carbon footprint grey hydrogen and the small-scale zero carbon footprint green hydrogen. This review provides the characteristics of different commercially available and new emerging processes to produce hydrogen from fossil fuels and biofuels, and the latest development in hydrogen storage and transport technologies as shown in figure 5. The review also discusses the progress of recent key advancements in carbon capture technologies, which are essential to the blue hydrogen production. The paper also critically reviews the costs and the carbon footprints of new technologies, discusses the necessary conditions to achieve large-scale production for marketable commercialization and offers a background to the fossil fuels industry to be part of the present energy transition. The techno-economic analysis of many recent papers has suggested that the oxygen-based process (such as auto-thermal reforming and partial oxidation) is the most economical to produce greenfield blue hydrogen.

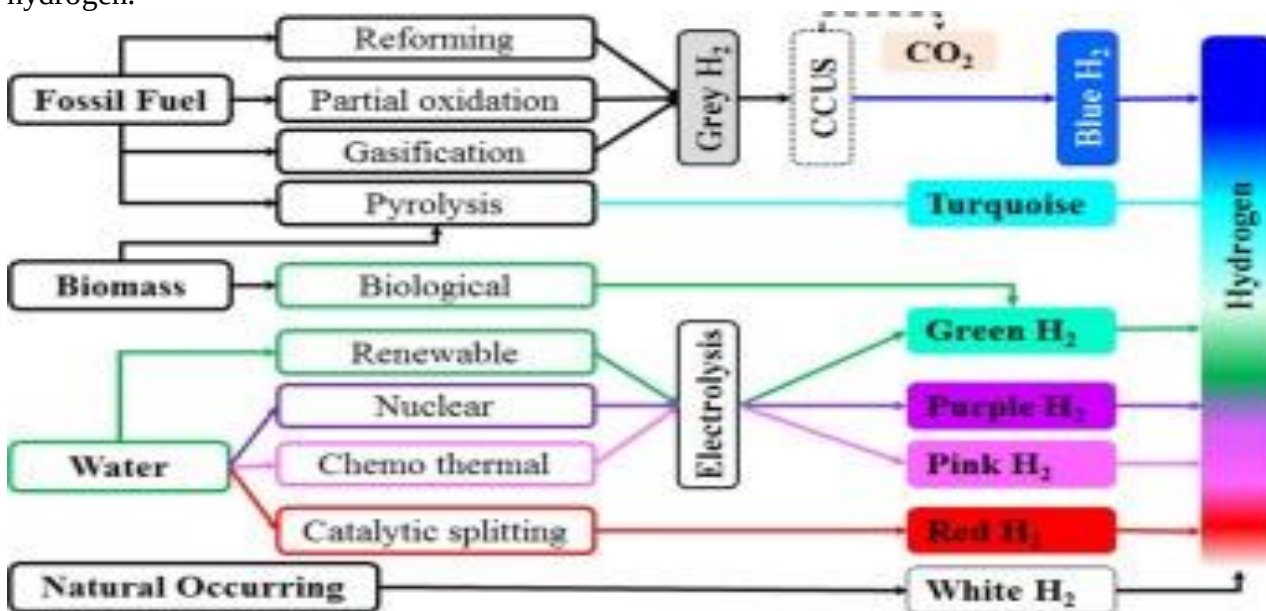


Fig. 5: Emerging Hydrogen Production Processes [14]

In a related study, [15][16] noted that advanced blue hydrogen technologies with the potential for combined power cycles that allow for flexible power generation and hydrogen production can help to reduce system costs by a further 12% with even higher negative emissions due to very high CO₂ capture ratios. These technologies were originally developed to integrate higher shares of wind and solar energy, but the cost for managing the intermittent hydrogen production due to an operational strategy for VRE integration was considerable, and the most cost-effective scenarios have lower VRE shares. The study concludes with advanced blue hydrogen technologies can lower system costs by 12% and allow negative CO₂ emissions due to increased efficiencies and CO₂ capture ratios. Blue hydrogen, obtained by retrofitting existing hydrogen technologies with carbon dioxide (CO₂) capture (CC) units, is a low-carbon alternative to gray hydrogen and a stepping-stone on the way to green hydrogen, which is produced from water electrolysis using renewable energy. Despite studies showing that cradle-to-plant-exit carbon dioxide (CO₂) emissions for blue hydrogen can be close to those of green hydrogen, lack of consistent assumptions in techno-economic and life-cycle assessments (e.g., plant location, feedstock, plant size) makes it difficult to draw direct comparisons and establish benchmark values. Thus, [17] overcomes these barriers by performing a literature review of recent environmental techno-economic analyses for blue hydrogen production. This includes the use of a consistent set of assumptions, system boundaries and definitions to standardise the data. This study offers a consistent approach to assess blue hydrogen production technologies, addressing inconsistencies with previous studies and enabling a fair comparison. The use of CC technologies in traditional hydrogen production processes can lead to a reduction in the life cycle CO₂ emissions of 60 % (similar to green hydrogen) while only increasing production costs by 30 % compared to unabated gray hydrogen.

In other studies [18][19], the authors observed that the key difference between blue hydrogen (and other types of hydrogen such as grey or green hydrogen) is the use of Carbon Capture, Utilisation and Storage (CCUS) technologies in the production process. Here, the carbon dioxide (CO₂) produced as a waste product is captured and either stored in geological formations or used for industrial purposes, thus reducing the carbon footprint. This leads to near-zero emissions hydrogen, in line with decarbonisation objectives. This research seeks to investigate innovative technologies for producing blue hydrogen and examine the integration with CCUS technologies. It will also examine the technical, economic and environmental aspects of blue hydrogen to determine its commercial viability and the potential of a scalable and low-emission hydrogen economy.

The world is transitioning to a sustainable energy future and blue hydrogen and carbon capture and storage (CCS) technologies are part of the solution to energy transition challenges. Blue hydrogen, which is produced from natural gas with the help of carbon capture and storage (CCS) technologies, and offers a way to reduce the carbon intensity of hydrogen production, a critical step in building a hydrogen economy. CCS technologies play a major role in the production of blue hydrogen, as it allows the capture and storage of the carbon dioxide released during hydrogen production. According to the excerpt from the paper by Bellona, blue hydrogen can drastically reduce the carbon footprint in comparison to conventional "gray" hydrogen production methods, but it still produces some emissions. Processes such as SMR and ATR are technologies used for blue hydrogen production from methane; however, ATR generally offers advantages in terms of lower CO₂ emissions per unit of hydrogen produced due to its higher energy efficiency and process characteristics. The use of CO₂ capture technologies greatly enhances the potential of ATR to reduce greenhouse gas emissions compared to traditional SMR [20][21].

Carbon Capture and Storage Technologies

The capture and compression of CO₂ after combustion is costly, both economically and in terms of energy and can account for more than 75% of the cost of Carbon Capture and Storage. To scale up CCUS to the level needed - from current 40 Mtpa (million ton per annum) to 5200 Mtpa in 2050 (Shell Sky scenario2) - cost reduction across the CCUS value chain is critical [22]. The authors also notes that, The Solid Sorbent Technology (SST) is a breakthrough technology which separates CO₂ from flue gas in a continuous Temperature Swing Adsorption (TSA) fluidized bed process using solid adsorbent. The technology simultaneously achieves > 90% CO₂ capture efficiency and > 95% CO₂ purity with low to no process related emissions and at lower capture costs compared to state-of-the-art liquid amines technology. This paper will present results of a 900 h pilot campaign with Lewatit VP OC 1065 adsorbent and its effect on the cost comparison with liquid amines. Successful piloting and completion of the test campaign resulted in advancement of the technology readiness level from TRL4 to TRL6.

The advancement of effective carbon capture technologies as mentioned in [23], is essential for climate change mitigation. Solid sorbents are gaining attention as a promising material for CO₂ capture, but traditional methods of shaping often lead to suboptimal performance and efficiency. This paper examines how additive manufacturing (AM) can address these challenges and enable the development of highly customised solid sorbents that are optimised for particular process conditions. The paper also reviews the traditional shaping techniques and their shortcomings and then examines the potential of AM in improving CO₂ capture and separation. Different AM strategies, such as direct and indirect printing, are discussed, and recent research showing the potential of 3D-printed solid sorbents to enhance gas flow, surface area and sorbent performance in adsorption are presented. The findings demonstrate that AM can greatly improve solid sorbent-based systems, and has the potential to be a viable method for greenhouse gas emissions reduction and climate change mitigation. ADA Environmental Solutions (ADA) is surveying the available sorbents and process equipment to evaluate the feasibility and speed up development of solid sorbents for post-combustion CO₂ capture. Consequently the research presented in [24] is being completed under a US Department of Energy (DOE) Cooperative Agreement, with additional funding provided by ADA, EPRI and a number of power industry partners. In the project 22 sorbents were obtained from developers and evaluated in laboratory-scale to determine sorbents for testing in a 1 kW slipstream pilot. Two sorbents were scaled-up to pilot-scale and one was tested in the 1 kW pilot, based on the laboratory results. Meanwhile,

existing commercial processes and equipment were investigated to select those that are promising for commercial-scale CO₂ capture.

METHODOLOGY

Assessment Framework

The most appropriate assessment approach based on the reviewed related studies would be a combined Techno-Economic Analysis (TEA), Life Cycle Analysis (LCA) and Performance Evaluation Framework, which includes technical efficiency, economic viability and environmental sustainability, the three aspects often underscored in the reviewed studies. This approach (as shown in table 1) follows a holistic assessment process, combining technical, economic and environmental considerations, as widely recommended in the assessment of CO₂ capture technologies. The Input and Technology layers consider sorbent properties and process conditions, which affect CO₂ capture efficiency. The Processing and Performance layers assess the effectiveness of the sorbents in blue hydrogen systems, specifically in terms of efficiency and purity of capture. The Economic and Environmental layers use Techno-Economic Assessment (TEA) and Life Cycle Assessment (LCA) to evaluate the cost and environmental impacts, thereby ensuring economic and environmental sustainability. The Innovation and Validation layers evaluate emerging technologies such as additive manufacturing and pilot testing to determine their readiness for upscaling. Finally, the Decision layer uses multi-criteria decision analysis to combine all metrics, allowing stakeholders to choose the most efficient and economical sorbent technology for producing blue hydrogen.

Table 1: Multi-Dimensional Framework for Assessing Advanced Sorbents for Efficient CO₂ Capture in Blue Hydrogen Plants

Framework Layer	Assessment Dimension	Key Indicators	Assessment Method	Expected Outcome
Input Layer	Feedstock & Process Conditions	Natural gas composition, CH ₄ conversion rate, CO conversion efficiency, flue gas composition, temperature, pressure	Process simulation (Aspen HYSYS), experimental data	Determines baseline CO ₂ generation and capture potential
Input Layer	Sorbent Material Properties	Adsorption capacity, selectivity, thermal stability, regeneration efficiency, surface area, porosity	Laboratory testing, material characterization techniques	Identifies suitability and performance potential of sorbents
Technology Layer	Sorbent Technology Type	Solid sorbents (e.g., zeolites, amine-supported sorbents), hybrid absorption-adsorption systems, TSA/VSA processes	Comparative technology analysis	Determines best-performing sorbent system
Processing Layer	Capture Mechanism Performance	CO ₂ capture efficiency (>90%), CO ₂ purity (>95%), hydrogen recovery (>99.9%), adsorption/desorption cycles	Pilot testing, TSA/VSA modeling	Evaluates technical effectiveness of sorbents
Processing Layer	Process Integration	Integration with SMR/ATR systems, hybrid CCS configurations, heat integration efficiency	System modeling and simulation	Improves overall plant efficiency and capture rate
Economic Layer	Capital Cost (CAPEX)	Sorbent cost, equipment cost, installation cost, scaling cost	Techno-Economic Analysis (TEA)	Determines initial investment requirements
Economic Layer	Operational Cost (OPEX)	Energy consumption, regeneration cost, maintenance	TEA, cost modeling	Assesses long-term operational feasibility

		cost, sorbent replacement cost		
Economic Layer	Profitability Metrics	Net Present Value (NPV), Payback Period, Levelized Cost of Hydrogen (LCOH), Return on Investment (ROI)	Financial modeling	Evaluates economic viability of sorbent systems
Environmental Layer	Carbon Emission Reduction	CO ₂ captured (kg CO ₂ /kg H ₂), lifecycle emissions reduction (~60%), residual emissions	Life Cycle Assessment (ReCiPe methodology)	Measures environmental sustainability
Environmental Layer	Resource Efficiency	Energy consumption, water usage, waste generation, process emissions	LCA and environmental impact analysis	Evaluates environmental footprint
Performance Layer	Operational Flexibility	Load adaptability (high/low load), scalability (100–400 TPD plants), response to fluctuating demand	Dynamic system simulation	Ensures adaptability in real-world conditions
Innovation Layer	Advanced Sorbent Design	Additive manufacturing (3D printing), customized structures, improved gas flow pathways	Experimental validation, AM techniques	Enhances adsorption efficiency and system performance
Validation Layer	Technology Readiness & Scalability	TRL level (e.g., TRL4–TRL6), pilot-scale validation, industrial deployment feasibility	Pilot plant testing, field validation	Confirms readiness for commercialization
Decision Layer	Multi-Criteria Decision Analysis (MCDA)	Trade-offs between efficiency, cost, and environmental impact	MCDA / Weighted scoring models	Supports optimal technology selection
Decision Layer	Sensitivity Analysis	Impact of natural gas cost, sorbent cost, CO ₂ price, hydrogen price	Sensitivity analysis tools	Identifies key economic drivers and risks

Research Design

This research adopted a systematic review comparative assessment design with Multi-Criteria Decision Analysis (MCDA) for the evaluation of advanced sorbent technologies for CO₂ capture in blue hydrogen production plants. The study created an evidence-based assessment framework, which involved identifying technical, economic, environmental, scalability and innovation indicators from the literature reviewed and then including them in a reproducible MCDA procedure.

The study design followed the following steps:

1. Identification and selection of relevant studies on CO₂ capture, blue hydrogen and advanced sorbents
2. Extraction and harmonization of Technical, economic and environmental indicators are
3. Definition and normalization of the assessment criteria
4. Implementation of a weighted MCDA process for the assessment of alternative sorbent technologies
5. Analysis of the robustness of the technology assessments, sensitivity and uncertainty a

The framework is based on an integrated TEA, LCA and performance-assessment approach suggested in the study. The framework takes into account feedstocks and process conditions, properties of the sorbent

material, capture efficiency, process integration, economic factors, environmental impacts, operational flexibility, innovation and technology readiness and combines the results in the MCDA process. The study made a distinction between framework development and technology assessment. The framework outlined the evaluation criteria for technologies, and the comparative assessment used the defined criteria and scoring process to evaluate selected advanced sorbents.

Systematic Review Search And Selection

A literature search process was used to identify works relevant to advanced sorbents, CO₂ capture and production of blue hydrogen. A literature search procedure was implemented to identify works relevant to the advanced sorbents and CO₂ capture and blue hydrogen production. The search strategy included major databases mainly Scopus, Web of Science, ScienceDirect, and Google scholar as well. Search strings included both terms pertaining to hydrogen production, and those of carbon capture and sorbent technologies.

A search string used include:

("blue hydrogen" OR "low-carbon hydrogen" OR "hydrogen production") AND ("CO₂ capture" OR "carbon capture" OR "CCS" OR "CCUS") AND ("sorbent" OR "adsorbent" OR "solid sorbent" OR "adsorption" OR "hybrid absorption adsorption")

The flow of the search and screening process is depicted using a PRISMA style flow diagram that details the number of records identified, duplicate records removed, records screened, and the number of full texts assessed and studies finally included as shown in figure 6.

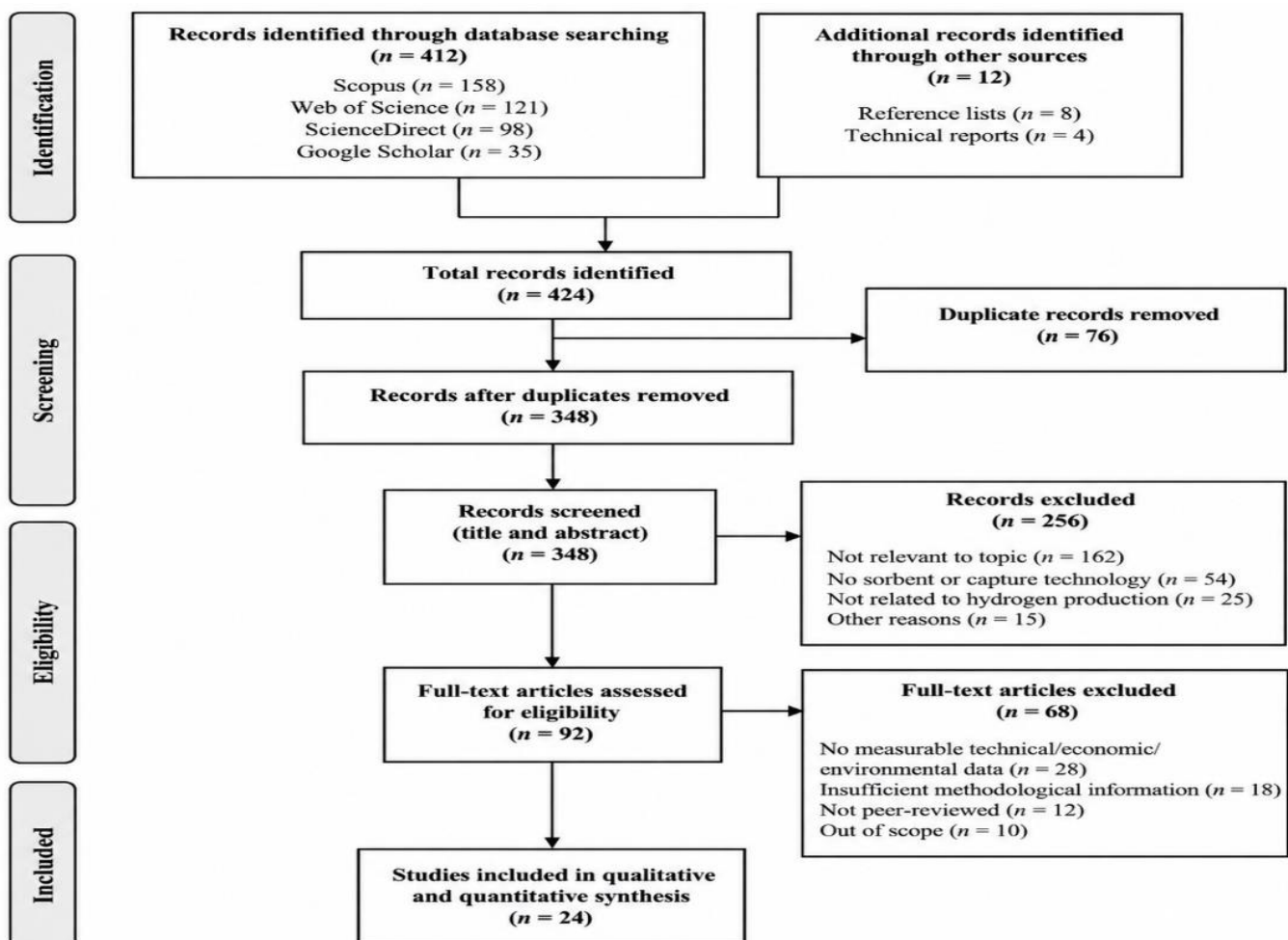


Figure 7: PRISIMA Diagram of the Study

Criteria Weighing and Scoring

To ensure reproducibility, each criterion was assigned an explicit weight. For the baseline assessment, equal weighting was adopted as illustrated in table 2. Equal weighting helped avoid introducing unsupported subjective preferences into the baseline analysis. A sensitivity analysis was performed by varying the weights (w_1 to w_5) to determine whether technology assessments remained stable under alternative stakeholder priorities.

Table 2: MCDA Criteria, Weights and Rationale for Assessing Advanced CO₂ Capture Sorbents

Criterion	Symbol	Weight	Percentage (%)	Rationale
Technical Performance	w_1	0.30	30	Central to determining CO ₂ capture efficiency, purity, hydrogen recovery and regeneration performance
Economic Viability	w_2	0.25	25	Important for determining CAPEX, OPEX, LCOH, NPV and commercial feasibility
Environmental Sustainability	w_3	0.20	20	Measures lifecycle emissions, energy use, water consumption and waste
Scalability	w_4	0.15	15	Captures TRL, pilot validation, scale-up potential and industrial applicability
Innovation	w_5	0.10	10	Represents technological novelty, advanced materials, hybridization and process innovation

Table 3 shows the comparative MCDA scores of three CO₂ capture technologies—amine absorption, solid sorbent and hybrid absorption–adsorption across five assessment criteria. The scores ranged from 1 (very poor) to 5 (very good). Amine absorption recorded scores of 4 for technical performance and 5 for scalability, but lower scores of 2 for environmental sustainability and innovation. The solid sorbent technology recorded the highest technical and innovation scores of 5, together with relatively high economic and environmental scores of 4, although its scalability score is 3. The hybrid system recorded scores of 5 for technical performance, economic viability and innovation, while obtaining scores of 3 and 4 for environmental sustainability and scalability, respectively.

Table 3: Comparative MCDA Performance Scores of Selected CO₂ Capture Technologies

Technology	Technical Performance	Economic Viability	Environmental Sustainability	Scalability	Innovation
Amine Absorption	4	3	2	5	2
Solid Sorbent	5	4	4	3	5
Hybrid Absorption–Adsorption	5	5	3	4	5

RESULTS AND DISCUSSION

Results

The heatmap in figure 6 shows the influence and performance of the assessment layers (Input, Technology, Processing, Economic, Environmental, Performance, Innovation, Validation, and Decision) in five evaluation criteria (technical performance, economic, environmental, scalability, and innovation). Red values (close to 5) represent strong influence or performance in a particular dimension, while green values represent low influence or performance. The heatmap shows that the Technology, Processing, and

Performance layers have high scores across all the dimensions, underscoring their importance in delivering effective CO₂ capture with advanced sorbents. The Economic and Environmental layers demonstrate high influence in cost and environmental performance, respectively, highlighting the role of economic and sustainability aspects in choosing sorbents. On the other hand, the Innovation and Validation layers have high values in scalability and innovation, emphasizing the impact of new technologies (such as advanced materials) and testing processes on enhancing performance. The Decision layer exhibits high values in many dimensions, suggesting its role in integrating all the assessment layers for optimal technology decision-making.

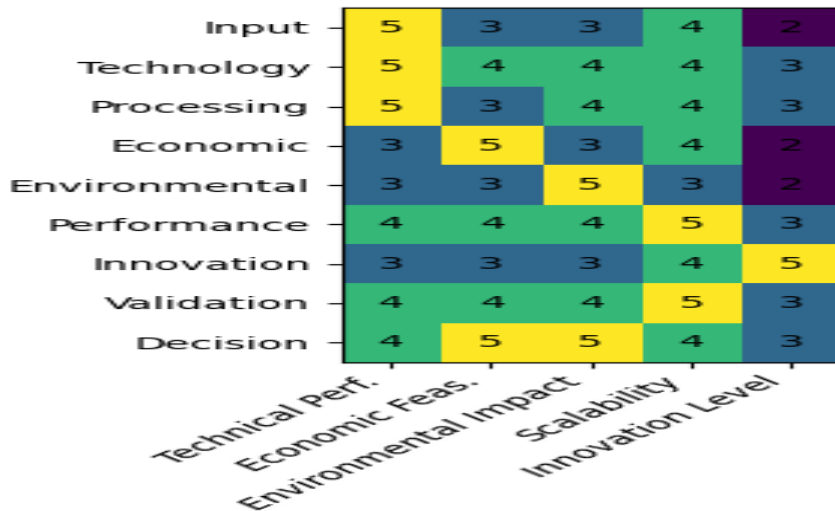


Fig. 6: Heatmap Diagram of the Assessment Framework

The bar chart in figure 7 shows the percentage contribution of each assessment layer to the overall evaluation of advanced sorbents for CO₂ capture. It highlights that Decision, Technology, Performance, and Validation layers have the highest contributions, indicating their critical role in achieving efficient and scalable carbon capture systems. In contrast, Environmental and Economic layers show relatively lower percentages, suggesting areas where further optimization is needed. Overall, the chart provides a quick comparison of how each layer influences the effectiveness of CO₂ capture in blue hydrogen plants.

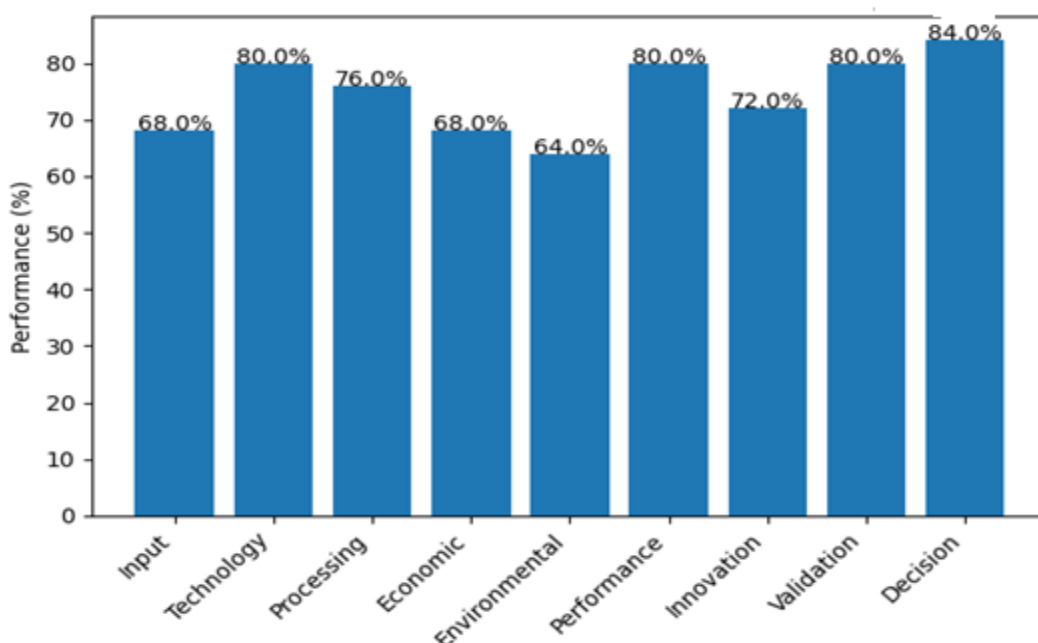
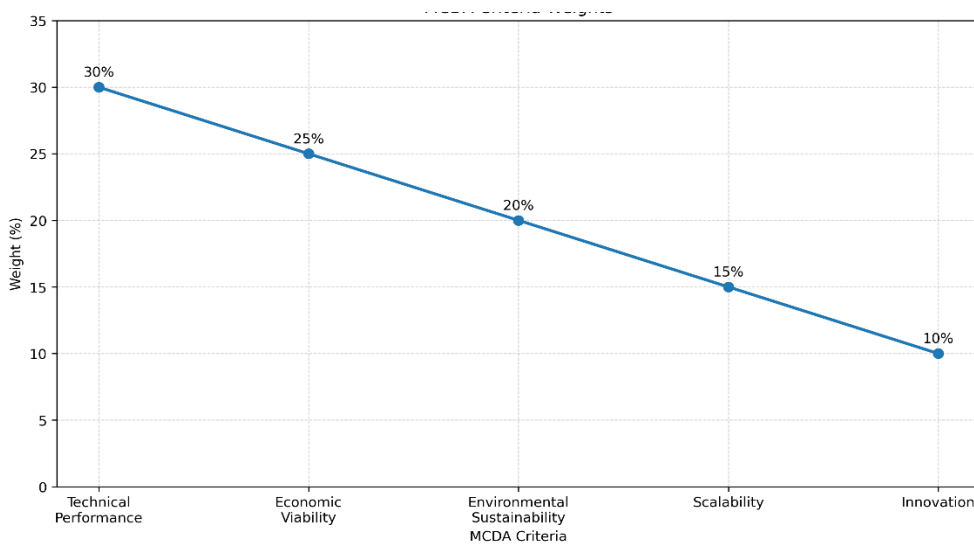


Fig. 7: Bar Chart Diagram of the percentage contribution across the Assessment Layers

The five criteria of MCDA for assessing the advanced sorbent technologies for CO₂ capture in blue hydrogen plants is represented using a line graph as shown in figure 8. The most important factors are the Capture efficiency, the purity of CO₂ and the hydrogen recovery and regeneration performance, which are emphasized to the highest degree with a Technical Performance of 30%. Economic Viability is the second highest at 25%, showing how economic and commercial viability is relevant. 20% was received by Environmental Sustainability, highlighting the entire lifecycle emission and resource footprint. 15% was allocated to Scalability, as technology readiness and upscale to industrial application are also equally important. The least important factor is innovation, with a weight of 10%, which signified the impact of technological novelty and the advanced development of materials.



DISCUSSIONS

1. The results show that technical performance and economic viability become key aspects of assessing the advanced sorbents for capturing CO₂ in the production of blue hydrogen. Technical performance was assigned the highest weight in the MCDA (30%), because the CO₂ capture efficiency, CO₂ purity, hydrogen recovery and hydrogen regeneration performance were of utmost importance. Economic viability was the most important, accounting for 25%, which included CAPEX, OPEX, sorbent cost, energy use and hydrogen production cost. Advanced solid sorbents and hybrid systems showed good technical and economic features but they were influenced by the operating conditions, plant configuration, sorbent features and economic assumptions. This implies that the technical efficiency is not the only criterion to be used for capturing technologies.
2. Reduced carbon footprint of blue hydrogen was allocated a weight value of 20% since it was not just about reducing CO₂ capture, but also about the effects on the environment. The reviewed studies showed potential for lower energy use and environmental impacts of conventional capture processes through the use of advanced sorbents and alternative capture configurations. There were dependences of energy source, sorbent production, regeneration requirements, water consumption, waste generation and LCA system boundaries on the environmental performance.
3. The weights for scalability and innovation were 15% and 10%, respectively. Scalability was included, suggesting that high performance at lab is not equal to success in industry. The results indicated that assessing commercial deployment involved factors like technology readiness level, pilot scale validation, long-term stability, cyclic performance, pressure drop and manufacturing requirements.
4. The framework offered a structured way of dealing with the compromises that arose when a technology was effective in one aspect of performance and not such good in another. Explicit weights, normalization procedures, aggregation equations, scores that can be traced back to their

sources and sensitivity analysis and uncertainty assessment enhanced the transparency and reproducibility of the evaluation. The resulting matrix was visualized using a heatmap in which the numerical values remained visible.

RECOMMENDATIONS AND FUTURE WORKS

Recommendations

Use of Advanced Solid Sorbent Technologies

The blue hydrogen industry should increasingly look at the advanced solid sorbent technologies (zeolites, amine supported sorbents) because this technology can deliver high CO₂ capture rate (>90%) and purity (>95%) with a lower energy consumption than traditional amine systems. This will increase the efficiency and reduce the operating cost of the system.

Use of Hybrid CO₂ Capture Systems

Industries should adopt a hybrid absorption-adsorption system, as the study has shown that this system will have better long term profitability, net present value and CO₂ capture efficiency. Such systems can combine the advantages of both liquid and solid CO₂ capture systems, and thus the best economic and environmental outcomes.

Integration of Standardized Assessment Frameworks

A consistent multi-criteria assessment framework, which incorporates techno-economic analysis (TEA), life cycle assessment (LCA) and performance assessment must be applied. This will enable technology comparison, deliver information to support decision-making, and guide policy and industrial implementation of effective CO₂ capture technology.

Future Work

1. Future work should include further improvements in the cost, performance, and scalability of advanced sorbents, such as novel techniques, such as additive manufacturing (3D printing) to enhance the adsorption capacity, surface area and flow rate through the sorbent bed.
2. Further work should include pilot- and industrial-scale testing and verification with real plants. This will help to determine the long-term performance, viability and costs, and hence help bridge the gap between the lab and the market.

CONCLUSION

This study has developed a comprehensive framework for assessing advanced sorbents for high-efficiency CO₂ capture in blue hydrogen production plants to replace the current fragmented approach. The holistic approach, with a multi-criteria framework that takes into account technical, economic and environmental factors, provides a more standardised and holistic evaluation of sorbent technologies. The findings show that advanced solid sorbents and hybrid absorption-adsorption processes have the potential to offer high efficiency for CO₂ capture, high regeneration efficiency and economic advantage. The framework supports better decision-making through the application of standardised and visual analysis methods, helping to understand the trade-offs involved. Finally, the research improves carbon-capture strategies by providing a straightforward and scalable approach to identify efficient, economic and environmentally sustainable sorbent systems, which will help the transition to low-carbon hydrogen production and other decarbonisation initiatives. The study contributes to knowledge by proposing a comprehensive assessment framework of advanced sorbents for CO₂ capture in blue hydrogen plants that accounts for technical efficiency, economic and environmental sustainability, in a single framework. It builds on other research which shows that solid sorbents can achieve more than 90% CO₂ capture efficiency and more than 95% purity with lower operating costs and low emissions than conventional amine scrubbing. The study also adds to the knowledge that

hybrid systems (absorption and adsorption) are more profitable and efficient in the long term, but the adsorption-only system has lower emissions and payback time. This study adds to the body of knowledge by building on the existing research that Techno-Economic Assessment (TEA) and Life Cycle Assessment (LCA) approaches, which makes it possible to compare efficiency, cost and environmental performance of different processes. It also reinforces that emerging technologies such as adsorption and membrane systems have the potential to affect the environment, but lack cost-efficiency.

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