Environmental Capacity in Industrial Clusters

Phase 4 Technical Annex 1 Literature review

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Literature Review

The structure of the following report gives a comprehensive and systematic exploration of the air quality and industrial emissions from low carbon technology, beginning with an introductory overview of the project to put the scope and significance in an environmental context. From there, it will expand upon general air quality and environmental considerations across the UK. To understand the current air quality and impacts on designated ecological sites the study focuses on the local context and the region where the HyNet Industrial Cluster is located. The following sections outline in more detail low carbon technology within the Hynet Industrial Cluster and further support with the introduction of Hynet Stakeholder Engagement Workshops, explaining the projects, purpose and objectives and how they support regional decarbonisation objectives.

Study Aims

The preceding Phase 3 literature review thoroughly examined the environmental and technological implications of hydrogen as a sustainable fuel and carbon capture technologies (Environment Agency, 2024 [1]). It assessed hydrogen applications such as NH_3 cracking, fuel switching to 100% hydrogen and its role in Medium and Large Combustion Plants. The review highlighted the environmental impacts of hydrogen leakage and emissions from carbon capture technologies, including nitrosamines and nitramines. It also identified knowledge gaps in understanding pollutants from hydrogen and CCS technologies, including their ecological and air quality effects within industrial clusters.

The Phase 3 review highlighted the importance of robust monitoring strategies, particularly for emerging amine-based solvents and hydrogen production methods. These foundational insights inform the current Phase 4 update by providing context for the evolving landscape of low-carbon technologies and their environmental considerations. The primary aim of this updated literature review is to advance the understanding of recent technological developments and environmental implications of two key areas in decarbonisation efforts: amine-based carbon capture systems and hydrogen as a low-carbon energy carrier. Building on the previous review (Environment Agency, 2024 [1], this study seeks to provide a more granular exploration of emerging monitoring technologies, solvent innovations, and strategies to mitigate environmental and health risks associated with these technologies.

Specifically, this review aims to:

1. Assess Advances in Amine-Based Carbon Capture Systems:
    - Explore baseline monitoring techniques for amines, focusing on their accuracy and capacity to detect harmful byproducts such as nitrosamines and nitramines.
    - Evaluate the technological advancements in real-time monitoring systems.
    - Investigate the environmental risks of amine degradation products and strategies for robust degradation management.

- Investigate the alternatives to Amine Based Carbon Capture solvents (e.g. CCapture).

2. Evaluate Hydrogen's Role in Sustainable Energy Systems:
    - Examine hydrogen's combustion characteristics, emphasising its dual potential to reduce carbon dioxide (CO_2) emissions while addressing challenges such as nitrogen oxide (NO_x) formation.
    - Investigate hydrogen leakage rates across its production, transportation, and storage phases, assessing their environmental and climate implications.
    - Analyse hydrogen integration into existing energy systems and its role in decarbonising sectors such as transportation, aviation, and industry.

3. Synthesise Insights into Health and Environmental Risks:
    - Identify potential health impacts linked to amine emissions and degradation products, including risks from nitrosamines and nitramines.
    - Evaluate the broader environmental impacts of hydrogen leakage, including its indirect greenhouse gas effects.
    - Highlight strategies to mitigate these risks through advanced monitoring technologies and operational best practices.

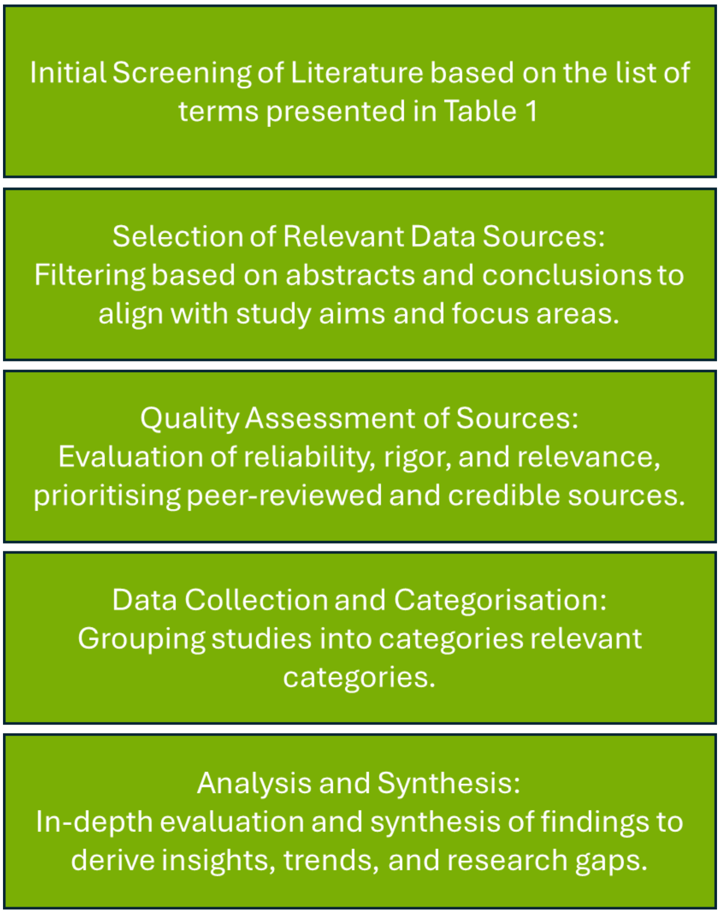
Methodology

This study employs a structured and systematic literature review methodology, modelled on the principles of Rapid Evidence Assessments (Collins et al., 2015 [2]), to compile, evaluate, and synthesise existing evidence on amine-based carbon capture and hydrogen technologies. Building on the foundations established in the Phase 3 literature review, which explored hydrogen applications, carbon capture technologies and associated environmental impacts within industrial clusters, this updated review focuses on recent advancements and emerging challenges. Figure 1 describes the procedure that was followed to select the most relevant available articles for the review.

The process began with an initial screening of literature, where predefined keywords related to carbon capture technologies, hydrogen use, and environmental impacts were applied across various databases such as Scopus, Web of Science, Google Scholar, and ScienceDirect, as well as credible industry reports and governmental publications. This stage ensured comprehensive coverage of recent advancements and relevant findings within the last five years. The selected studies underwent a rigorous quality assessment, focusing on source credibility, methodological rigor, relevance to the research aims, and publication reliability. Priority was given to peer-reviewed articles and reports from reputable organisations to ensure the robustness of findings. After initial screening and quality filtering, data from the studies were systematically categorised into thematic areas such as monitoring techniques for amines, hydrogen combustion characteristics, and associated environmental challenges. During this phase, efforts were made to prioritise studies from recent years to capture current innovations and align findings with the state-of-the-art technologies.

Finally, the selected studies were subjected to a comprehensive analysis and synthesis process. This involved extracting key insights, identifying technological trends, and synthesising findings to form a coherent narrative that addresses both the opportunities and challenges of amine-based carbon capture and hydrogen systems. This iterative approach, emphasising both breadth and depth, ensures the outcomes are current, relevant, and aligned with the objectives of the study.

Figure 1: Study Methodology Outline



The source search terms, detailed in Table 1, were used to perform the initial screening of literature related to amine-based carbon capture technologies, hydrogen's role in reducing greenhouse gas emissions and their associated impacts on health, environment and climate change. The literature search included systematic reviews of reports and peer-reviewed articles from scientific databases such as Google Scholar, Scopus, Science Direct, and Web of Science. Search terms were carefully selected to align with the study's focus on advancements in solvent innovations, process optimisations, health risks, and implications for climate change. Synonyms and alternate versions of keywords were also utilised to enhance the breadth of the search. Initially, keywords were used individually, and then logically combined (using 'OR' and 'AND') to identify the most relevant abstracts and studies. This systematic approach ensured comprehensive coverage of the most recent and pertinent findings for review.

Table 1: Review Search Terms

Search Terms for Web	Search Terms for Academic Journals
Amines in carbon capture systems	Amine degradation AND emissions AND monitoring
Carbon Capture Technologies	Carbon capture AND amines AND nitrosamines
Advanced monitoring techniques for amines	Advanced monitoring AND amines AND real-time detection
Health risks of amine emissions	Nitrosamines AND nitramines AND health risks
Amine degradation in power plants	Amine emissions AND monitoring AND modelling
Amine emissions in power plants	Amine degradation AND nitrosamines AND monitoring
Environmental impacts of amine emissions	Amine emissions AND real-time monitoring
Amine-based carbon capture	Amine emissions AND ecosystems OR environmental impacts
Nitrosamines and health risks	Ionic liquids OR deep eutectic solvents AND carbon capture
Advanced monitoring techniques for amine emissions	Non-amine solvents AND energy efficiency AND environmental benefits
Innovative amine-based capture solutions	Nitramines AND Nitrosamines AND health risks
Transitioning from amine-based to non-amine solutions	Amine alternatives AND decarbonisation strategies
Climate change impacts of carbon capture	Hybrid solvents AND regeneration energy AND carbon capture
	Long-term effects AND amine emissions AND ecosystems OR human health
	Hydrogen leakage AND climate impacts
	Hydrogen production AND storage AND challenges
	Hydrogen leakage AND air quality OR atmospheric chemistry
	Hydrogen AND air quality AND impacts
	Hydrogen storage AND leakage AND geological risks
	Amine scrubbing AND performance AND assessment

The initial search of the databases yielded 605 citations. The first step in refining this pool involved removing duplicates, significantly reducing the number of articles. After removing the duplicates, we conducted a preliminary screening based on titles and abstracts, which led to further exclusion of articles that did not align with the scope of our review. This process resulted in 302 articles identified as potentially relevant and available for full-text retrieval.

During the detailed review of these articles' journal abstracts or website summaries, we applied specific inclusion criteria, leading to further exclusions: 213 articles were excluded for the following reasons:

- 108 articles were excluded due to their focus being outside the scope of the literature review;

- 80 articles were excluded because they were old articles (before 2020) without providing any useful research data; and
- 30 articles were excluded for not providing sufficient detail on the methodologies or outcomes relevant to our study objectives or were review articles without original research data.

Table 2 shows the focus areas and the number of studies included in the review. Some studies focus on more than one category or offer other relevant insights to the literature review. The following section sets out the findings of the literature review.

Table 2: Summary table of the Focus Areas and the number of studies

Focus Area	Count
Hydrogen	20
H_2 Leakage	10
Amine-Based Carbon Capture Technologies and Alternatives	20
Non-Amine Based Carbon Capture	15
Health, Environmental and Climate Risks	11
Studies covering more than one category	8
Total	84

Hydrogen

Integration of Existing and New Insights into Hydrogen Research

The role of hydrogen as a transformative energy carrier has been consistently highlighted in recent literature, with its versatility spanning applications in industrial decarbonisation, transportation, and power generation. For example, in industrial applications, hydrogen has been identified as a key enabler for decarbonising the steel sector through Direct Reduced Iron (DRI) processes, which use hydrogen instead of coal to reduce iron ore. This approach eliminates up to 90% of CO_2 emissions compared to traditional blast furnace methods, making it a cornerstone of net-zero industrial strategies (Griffiths et al., 2021 [3]). Similarly, green hydrogen is being adopted in ammonia synthesis, replacing traditional fossil fuel-based methods and significantly reducing lifecycle emissions (Osman et al., 2021 [4]). In transportation, hydrogen-powered fuel cell electric vehicles (FCEVs) have demonstrated significant potential, achieving ranges of over 500 km with zero CO_2 emissions, supported by compressed hydrogen storage systems whose costs are projected to reduce to $8/kWh by 2030 (Gómez & Santos, 2023 [5]). Additionally, hydrogen is being integrated into power systems to enable the storage of surplus renewable energy, providing a reliable and flexible energy supply, particularly during periods of low renewable output (Yue et al., 2021 [6]).

The EU-funded HyPSTER project further exemplifies hydrogen's transformative role by demonstrating the feasibility of underground hydrogen storage in salt caverns. This project integrates renewable energy with large-scale hydrogen storage to support decarbonisation across industrial and mobility sectors, paving the way for scalable and cost-efficient hydrogen storage solutions (HyPSTER, 2023 [7]). Earlier studies emphasised hydrogen's potential to enhance combustion efficiency and reduce greenhouse gas emissions when used in blends with conventional fuels or as a primary fuel in advanced combustion systems (Environment Agency, 2024 [1]). For example, prior findings detailed the successful integration of hydrogen in fuel cells and internal combustion engines, demonstrating substantial reductions in pollutants like carbon monoxide (CO), CO_2, and hydrocarbons (Environment Agency, 2024 [1]). This foundational understanding set the stage for further exploration into advanced blending strategies and emission control mechanisms.

The HyNet Industrial Cluster provides a real-world example of this potential, with its hydrogen pipeline and storage infrastructure supporting decarbonisation in the North West of England and North Wales. For instance, HyNet’s salt cavern storage facility in Cheshire, designed to store 35,000 tonnes of hydrogen, offers a scalable solution for balancing seasonal energy variability and ensuring reliable industrial supply. These facilities are integrated with the Stanlow Manufacturing Complex, where hydrogen is produced and distributed through a 62-mile Cadent pipeline.

Expanded Understanding of Combustion Characteristics and NOx Mitigation

Building on earlier findings, recent research highlights the dual challenges and opportunities presented by hydrogen's unique combustion properties. Notably, hydrogen's high flame speed and broad flammability range enhance stability in lean-burn conditions but necessitate advanced designs to mitigate flashback and NO_x emissions. Results from newer studies highlight significant reductions in CO and CO_2 emissions in gas turbines using hydrogen blends, up to 96.63%, although NO_x emissions remain a challenge (Tamang and Park, 2023 [8]). Emerging strategies, such as staged combustion and exhaust gas recirculation (EGR), show promise in addressing these challenges, achieving up to 62% NO_x reduction in controlled environments (Wu et al., 2023 [9]). These advancements point toward the feasibility of hydrogen integration in various systems with optimised burner designs and emission control strategies.

Within HyNet, hydrogen combustion applications, such as those trialled at Pilkington Glass and Unilever, highlight how industrial processes can transition to hydrogen use while managing emissions. These trials provide critical insights into burner design and emission control mechanisms that will be essential for scaling hydrogen adoption.

Hydrogen Storage and Utilisation

Hydrogen storage is a cornerstone of the hydrogen value chain, enabling the large-scale deployment of renewable energy while addressing its intermittency. As hydrogen becomes a central pillar of global decarbonisation strategies, the ability to store it safely and efficiently at scale is critical. Among various storage methods, underground hydrogen storage (UHS) in geological formations such as salt caverns, depleted hydrocarbon reservoirs, and aquifers offers scalability to meet industrial and energy grid demands. UHS provides a long-term, cost-effective solution, supporting energy system resilience, balancing seasonal energy variability, and integrating renewable hydrogen into energy-intensive sectors such as transportation, industry, and power generation (Fuentes & Santos, 2023 [10]; Simon et al., 2015 [11]; Zivar et al., 2020 [12]; Tarkowski, 2019 [13]).

Key issues in UHS include hydrogen leakage due to its small molecular size, which increases risks in porous formations like aquifers. Material embrittlement in pipelines and storage wells necessitates advanced materials and coatings to maintain infrastructure integrity (Zivar et al., 2020 [12]). Additionally, microbial activity in aquifers can result in hydrogen losses through methanation and sulphate reduction. These challenges underscore the importance of continued innovation in materials science and operational techniques, along with policy interventions to encourage the adoption of UHS (Pan et al., 2021 [14]).

Recent literature expands the scope of hydrogen applications to sectors like aviation and maritime transportation, where hydrogen and its derivatives, such as ammonia, are being explored for zero-carbon propulsion. For instance, the reduction in lifecycle emissions through hydrogen-powered sustainable aviation fuels (SAFs) and hydrogen-ammonia blends in shipping presents a viable pathway for decarbonising these challenging sectors (IEA, 2024 [15]). However, persistent challenges like hydrogen embrittlement in materials, leakage across the supply chain, and the economic barriers to green hydrogen production highlight critical areas for innovation (Environment Agency, 2024 [1]; Wei et al., 2024 [16]; Giacomazzi et al., 2023 [17]). Earlier findings on system retrofitting and cost-effective production align with these newer insights, reinforcing the necessity of a multi-faceted approach to advancing hydrogen technologies (Environment Agency, 2024 [1]).

HyNet's integrated network addresses these issues through robust infrastructure planning. While the Cadent hydrogen pipeline facilitates direct delivery to industrial users, road-based transportation of hydrogen raises additional concerns. Recent developments in the UK hydrogen strategy emphasise the importance of robust frameworks for transport and storage to meet its ambition of up to 10 GW production by 2030. The integration of innovative monitoring technologies and the rollout of advanced hydrogen-compatible materials in pipelines reflect ongoing efforts to mitigate leakage risks.

While blue hydrogen continues to face scrutiny for its lifecycle emissions, amplified by methane leakage and underperforming carbon capture technologies, green hydrogen advancements, particularly in electrolyser efficiency, are reducing its cost barrier and positioning it as a scalable alternative. These innovations underscore the shift towards sustainable hydrogen production and storage strategies that prioritise environmental and economic feasibility (HM Government, 2023 [18]; Schlissel and Juhn, 2023 [19]). Potential leakage and increased vehicle emissions could offset the environmental benefits of hydrogen use. Addressing these risks will require advanced monitoring systems and sustainable logistics solutions (Reuters, 2024 [20]).

Case studies of hydrogen storage projects, such as Spain’s HyUnder and France’s HyPSTER, further illustrate the transformative potential of hydrogen in decarbonising multiple sectors. The HyUnder project identified 24 salt caverns suitable for hydrogen storage in Spain, with applications spanning industry, natural gas blending, and transport. By 2050, hydrogen storage in Spain could support up to 38% of the passenger car fleet’s fuel demand, demonstrating its integration into the broader hydrogen ecosystem (Simon et al., 2015). Similarly, Germany’s extensive gas storage infrastructure can be repurposed for large-scale hydrogen storage, contributing significantly to national decarbonisation strategies (Alms et al., 2023 [21]; HyPSTER, 2024 [7]; European Commission, 2024 [22]).

Environmental and Safety Implications of Hydrogen

Hydrogen, while often lauded as a clean energy carrier, presents indirect greenhouse gas challenges through its impact on atmospheric chemistry. By interfering with oxidative processes, hydrogen prolongs the atmospheric lifetime of methane and increases concentrations of tropospheric ozone and stratospheric water vapor, thereby contributing to indirect warming effects (Ocko and Hamburg, 2022 [23]). Modelling studies suggest that a global hydrogen leakage rate of 10% could lead to an additional warming of up to 0.27°C by 2050, potentially offsetting the climate benefits of transitioning to hydrogen systems (Ocko and Hamburg, 2022 [23]). Hydrogen's radiative efficiency, which is 200 times greater than that of CO_2 per unit mass in the short term, highlights the inadequacy of conventional metrics such as GWP-100 for assessing its climate impacts (Ocko and Hamburg, 2022 [23]).

To mitigate these impacts, HyNet incorporates advanced sealing technologies and real-time monitoring systems across its pipeline and storage infrastructure. These measures are designed to minimise hydrogen leakage, ensuring that the climate benefits of transitioning to hydrogen systems are realised. By proactively addressing leakage risks, HyNet aims to ensure that the radiative forcing associated with hydrogen's indirect effects does not offset the climate benefits of transitioning to hydrogen systems. Furthermore, the implementation of leak detection and repair protocols (EPA, 2007 [24]) within the cluster directly contributes to reducing currently emitted indirect greenhouse gases, reinforcing the environmental sustainability of hydrogen as a clean energy carrier.

Hydrogen's small molecular size and low viscosity make it highly prone to leakage throughout its value chain. Leakage rates ranging from 1% to 10% have been reported, depending on the infrastructure used for storage and transportation (Ocko and Hamburg, 2022 [23]). Geological storage also poses challenges, as hydrogen's high mobility and lower density compared to natural gas or CO_2 enable extensive lateral movement in depleted oil reservoirs and saline aquifers, complicating containment efforts (Delshad et al., 2022 [25]). Upon leakage, hydrogen forms flammable vapor clouds, with dispersion heavily influenced by environmental conditions such as wind patterns. Simulations using liquid helium as a surrogate have demonstrated these effects, highlighting the need for robust containment strategies (Shu et al., 2022 [26]).

HyNet addresses these risks through the use of advanced materials in its salt cavern storage facility and pipeline infrastructure, along with optimised insulation and venting systems. These measures are critical for ensuring the safety and reliability of hydrogen transport and storage, mitigating flammability risks and potential vapor cloud formation during leaks.

In terms of safety, hydrogen storage presents significant engineering challenges. Smaller liquid hydrogen tanks, for instance, experience faster pressure build-up due to higher surface-to-volume ratios, leading to increased boil-off losses. Optimised insulation and venting systems have been shown to mitigate these risks effectively (Matveev and Leachman, 2023 [27]). Additionally, engineering controls such as wind management strategies and infrared thermal imaging have proven effective in minimising risks associated with hydrogen dispersion and diffusion (Shu et al., 2022a and 2022b [26] [28]). These advancements are critical in realising hydrogen's potential as a cleaner energy carrier while addressing its associated safety hazards and indirect contributions to climate change.

While hydrogen combustion is often promoted for producing only water vapor, it also generates NO_x, including nitric oxide (NO), nitrogen dioxide (NO_2), and nitrous oxide (N_2O), due to the high temperatures required for combustion. NO_x formation is primarily driven by the Zel'dovich mechanism, where atmospheric nitrogen reacts with oxygen under intense thermal conditions (Boningari and Smirniotis, 2016 [29]). The higher flame temperature of hydrogen, compared to methane and other fuels, exacerbates this process, potentially increasing NO_x emissions by 30%-40% if not mitigated by advanced combustion technologies (HM Government, 2024 [30]).

Health impacts from NO_x emissions include acute respiratory irritation, exacerbation of asthma, and increased hospital admissions due to airway inflammation. Prolonged exposure to NO_2 is linked to chronic cardiovascular issues and developmental concerns, particularly in children. NO_x also contributes to the formation of fine particulate matter ($PM_{2.5}$), which is associated with premature mortality and reduced lung function (Jin et al., 2023 [31]). Cytotoxicity studies demonstrate that exposure to NO_x leads to oxidative stress at the cellular level, implicating its role in broader systemic health issues (Jin et al., 2023 [31]).

Environmental impacts are equally significant. NO_x emissions are precursors to ground-level ozone and acid rain, which alter soil pH and leach nutrients vital for ecosystems. Nitrogen deposition from NO_x disrupts biodiversity in nitrogen-sensitive habitats, such as grasslands and wetlands, reducing ecosystem resilience. Moreover, nitrous oxide's long atmospheric lifetime and high global warming potential amplify its role in long-term climate change, with effects that could offset some of hydrogen's anticipated decarbonization benefits if not controlled effectively (Boningari and Smirniotis, 2016 [29]).

Mitigation strategies are advancing to address these challenges. Technologies such as Moderate or Intense Low-oxygen Dilution (MILD) combustion can reduce peak flame temperatures and lower NO_x formation rates by creating more uniform combustion zones (Iavarone and Parente, 2020 [32]). Selective catalytic reduction (SCR) systems, employing ammonia or urea, are already capable of reducing NO_x emissions by over 90%, making them essential for hydrogen-fired systems in industrial applications (HM Government, 2024 [30]). Furthermore, low-NO_x burner technologies, tailored for hydrogen's combustion characteristics, are being deployed to meet evolving emission limit values (ELVs) under directives such as the Medium Combustion Plant Directive (MCPD).

In the HyNet region, where hydrogen infrastructure is expanding, the integration of advanced combustion technologies is vital. With regional climate projections indicating increases in annual maximum temperatures of up to +2.46°C by mid-century, combustion systems will face enhanced thermal conditions conducive to greater NO_x formation. Real-time emissions monitoring, combined with policy measures to enforce stringent NO_x standards, will be critical for balancing hydrogen's role as a clean energy carrier with its environmental and public health responsibilities.

Carbon Capture

Carbon Capture Solvents

Monitoring and Advances in Amine-Based Carbon Capture Systems

Monitoring amines in carbon capture systems is essential for understanding their environmental and health impacts while ensuring compliance with operational standards. The complex chemistry of amines, particularly their degradation into harmful compounds such as nitrosamines and nitramines, presents challenges in establishing accurate baselines. Advanced technologies such as Proton Transfer Reaction Mass Spectrometry (PTR-MS), Fourier Transform Infrared Spectroscopy (FTIR), and chemometric modelling have significantly enhanced monitoring precision and scope (Wagaarachchige et al., 2023 [33]; Einbu et al., 2021 [34]). Additionally, innovative extraction methods like Head-Space Solid-Phase Micro Extraction (HS-SPME) have been pivotal in detecting volatile degradation products such as pyrazines, often overlooked by traditional approaches (Cuzuel et al., 2015 [35]). The integration of techniques such as Gas Chromatography-Mass Spectrometry (GC-MS) and Liquid Chromatography with Tandem Mass Spectrometry (LC-MS/MS) has further expanded the ability to identify previously undetected degradation products. A novel photolysis-chemiluminescence method has demonstrated remarkable progress in monitoring Total N-Nitrosamines (TONO), achieving detection limits as low as 0.02 µM, with recovery rates exceeding 100% for specific nitrosamines such as NDMA and NPIP (Ullah et al., 2024 [36]).

At the Technology Centre Mongstad (TCM) in Norway, PTR-MS has been effectively used for real-time monitoring, showcasing excellent sensitivity in detecting trace levels of monoethanolamine (MEA) and nitrosamines down to parts-per-billion (ppb) concentrations (Wagaarachchige et al., 2023 [33]). Meanwhile, oxidative degradation studies in waste-to-energy plants have underscored the importance of robust baseline measurements for tracking solvent health and environmental emissions. Techniques like Ion Chromatography (IC) have been instrumental in identifying degradation byproducts such as formate and acetate, while impinger sampling coupled with IC or LC-MS has strengthened the quantification of low-concentration compounds. However, these approaches are resource-intensive and require extensive calibration to maintain accuracy (Neerup et al., 2023 [37]). The identification of 26 previously unreported degradation products in pilot-plant studies highlights the ongoing need for adaptable and comprehensive monitoring frameworks (Cuzuel et al., 2015 [35]).

Advanced monitoring technologies have improved amine detection and degradation tracking. PTR-MS has played a critical role in continuous monitoring, identifying novel degradation products like nitromethane and pyrazine (Ullah et al., 2024 [36]). Its integration with gas chromatography has enhanced both sensitivity and throughput, making it suitable for industrial-scale applications (GHGT-15, 2021a and 2021b [38] [39]). FTIR spectroscopy, although effective at monitoring amines at parts-per-million (ppm) levels, has struggled with detecting low-concentration compounds. Enhanced setups incorporating chemometric tools such as Partial Least Squares Regression (PLS-R) have improved FTIR's detection capabilities over time (Einbu et al., 2021 [34]). Additionally, photolysis-chemiluminescence methods have allowed real-time measurement of nitrosamines with high specificity, distinguishing these compounds from chemically similar groups in emission streams (Zhu et al., 2013 [40]). Optimised parameters, including a UV dose of 10.4×10^3 mJ/cm^2 and evaporator temperatures up to 250°C, have enabled a 95% photodecomposition efficiency, further demonstrating its industrial applicability (Ullah et al., 2024 [36]).

Despite these advancements, challenges in baseline monitoring remain. Sample stability during collection is a persistent issue, as condensation, thermal degradation, and adsorption often compromise data integrity (Liu et al., 2014). Equipment durability is also a concern, with continuous exposure to corrosive flue gases and solvents leading to wear and tear, complicating long-term monitoring efforts (Neerup et al., 2023). Through simulations in Aspen HYSYS, Øi et al. (2023) [41] demonstrated that optimising variables such as inlet pressure, temperature, and heat exchanger efficiencies significantly improves the cost-effectiveness and operational feasibility of amine-based carbon capture processes. For example, reducing the minimum temperature difference in heat exchangers to 15°C decreased capture costs to €20.9 per ton of CO_2. However, achieving these optimisations in industrial-scale operations demands investments in high-temperature-resistant materials and flexible process configurations to handle variability in gas compositions (Øi et al., 2023 [41]).Furthermore, the lack of standardised reference methods for amine-based systems has resulted in inconsistent results across regions. While European standards such as EN 15259 provide general guidance, they do not address the specific needs of amine monitoring (Jarvinen et al., 2012 [42]).

Future Directions in Monitoring Practices

Future advancements in amine monitoring will likely focus on adopting advanced online systems to address existing challenges and improve efficiency. For instance, the Absorber Continuous Emission Monitoring System (ACEMS) facilitates continuous, real-time data collection for amine and nitrosamine levels, reducing reliance on manual sampling and improving the reliability of baseline measurements (Einbu et al., 2021 [34]). The integration of chemometric models in pilot plants has also shown potential for adaptive monitoring, capturing real-time variations in solvent degradation and improving overall system efficiency (Wagaarachchige et al., 2023 [33]).

Efforts to standardise methods for monitoring amines and their byproducts are underway, with the adoption of advanced techniques such as real-time FTIR spectroscopy and standardised protocols like EN TS 14791. Hybrid systems that integrate PTR-MS with gas chromatography have been instrumental in improving both sensitivity and throughput for large-scale operations, addressing variability in operational conditions and ensuring regulatory compliance (GHGT-15, 2021a and 2021b [38] [39]). As these technologies and frameworks evolve, they are expected to play a crucial role in establishing robust, efficient, and standardised monitoring practices for amine-based carbon capture systems.

Emerging Carbon Capture Solvents and Innovative Approaches

Advancements and Innovations in Carbon Capture Systems

Amine-based carbon capture technologies have undergone significant advancements aimed at improving solvent performance, reducing energy consumption, and mitigating environmental impacts associated with solvent degradation. Key innovations include the development of blended systems, hybrid solvents, and optimised process parameters, all of which have collectively enhanced the efficiency and sustainability of carbon capture operations. Advanced solvent systems have been particularly transformative, revolutionising CO_2 capture by optimising absorption capacity and minimising energy demands. For example, MEA degradation studies revealed a weekly loss rate of 2.5 ± 1.1 g/L, emphasising the importance of robust degradation management strategies to mitigate operational risks (Vevelstad et al., 2017 [43]). Blended amines, such as AMP+TBMEA and MEA with sterically hindered amines, have shown superior performance by achieving CO_2 removal rates of 87–95% and phase-splitting efficiencies above 95%, while significantly lowering regeneration heat demand compared to conventional MEA systems (Hatta et al., 2022 [44]). Hybrid solvents, such as amine-ionic liquid blends like MEA-[TBA][Br], have demonstrated reduced viscosity and energy requirements for regeneration, maintaining high absorption rates and resistance to degradation (Jayaraman & Perumal, 2023 [45]). The study by Li et al. (2022) [46] highlighted that tertiary amines like triethanolamine (TEA) consistently yield higher formate conversion rates, reaching up to 82.6% at specific CO_2 loading levels. This is attributed to bicarbonate being the sole CO_2 absorption product in TEA solutions, which is more favourable for hydrogenation compared to carbamate species present in primary and secondary amines like MEA and DEA (Li et al., 2022 [46]). This finding aligns with the broader need for tailored amine solutions in capture processes to enhance product yield while reducing inefficiencies associated with competing reactions. While solvents like CESAR1 exhibit improved resistance to degradation and operational longevity compared to MEA, their higher volatility necessitates advanced emissions management strategies, such as dry-bed and turbulent spray-scrubbing, to meet environmental compliance (Weir et al., 2023 [47]).

The GCCmax solvent is another promising innovation, outperforming MEA by reducing heating duties by 25.4-29.4% and solvent flow rates by 58.8-64.7%, while consistently achieving 90% CO_2 capture efficiency during pilot tests (Sharifzadeh and Shah, 2015 [48]). Biphasic solvents, such as the MAE/DGM/H_2O system, further enhance energy efficiency, cutting regeneration energy by 40% and achieving a cyclic CO_2 capacity of 1.32 mol/L (Hong et al., 2024 [49]). Non-aqueous amine hybrid solvents, such as MEA blended with methanol, have also shown substantial reductions in regeneration energy up to 49%

compared to aqueous MEA systems, although this comes at the cost of reduced cyclic capacity (Alkhatib et al., 2020 [50]).

Optimising process parameters has proven instrumental in enhancing the performance and energy efficiency of carbon capture systems. Techniques like Model Predictive Control (MPC) allow flexible system operation to accommodate fluctuating outputs from power plants (Aghel et al., 2022 [51]). Blended and hybrid solvents have demonstrated energy savings of 20-40% in regeneration processes compared to MEA, while phase-change systems have further boosted CO_2 capture efficiency, achieving over 90% capture under optimised conditions (Chen et al., 2022 [52]; Liu et al., 2021 [53]). Simulations conducted in the study reveal that MEA achieves a capture efficiency of 99% in shifted gas streams but is less effective in flue gas streams, achieving only 70% under typical operating conditions (Hamed et al., 2023 [54]). These findings show the importance of tailoring carbon capture systems to specific emission streams for maximised efficiency. Nitrosamine recovery rates exceeding 95% under optimised configurations highlight the role of advanced operational strategies in minimising environmental impacts (Vevelstad et al., 2017 [43]).

Transitioning to Non-Amine Based Alternatives

Despite these advancements, the limitations of amine-based solvents have prompted researchers to explore non-amine-based alternatives that offer reduced energy demands, lower emissions, and broader environmental benefits. These alternatives leverage novel chemistries and sustainable materials to address the challenges of conventional systems. For instance, dual-functionalised ionic liquids, such as [DMAPA][TZ] combined with polyethylene glycol dimethyl ether (NHD), have achieved energy consumption rates as low as 0.662 GJ/t CO_2, significantly lower than MEA's 1.44 GJ/t, while minimising risks associated with corrosion (Mao et al., 2024 [55]).

KHCO3 CD-MOF stands out as a promising candidate due to its unique CO_2 chemisorption pathway involving bicarbonate formation at nucleophilic hydroxide sites. Compared to traditional amine-functionalised materials, KHCO3 CD-MOF exhibits a stronger binding affinity for CO_2, as evidenced by a free energy of adsorption (-ΔGads) value of 19.4 kJ/mol at 40 °C. This performance is further enhanced by its ability to retain structural integrity and CO_2 capture efficiency (over 90% retention) even after 115 adsorption-desorption cycles, showcasing exceptional durability (Zick et al., 2022 [56]).

The development of pore-optimized MOF-808 membranes, cross-linked with polyvinylamine (PVAm), represents another significant advancement in non-amine-based alternatives. These membranes achieved remarkable CO_2 permeance of 2753 GPU and CO_2/N_2 selectivity of 181 under a 2-bar system, demonstrating a 200% improvement in CO_2 permeability and a 120% increase in selectivity compared to unmodified membranes. Additionally, the MOF-808@PVAm system maintained stability in simulated flue gas containing impurities like SO_2 and O_2, with only 10–17% reductions in performance, which were largely reversible. These characteristics highlight MOF-808@PVAm's potential for scalable, high-performance CO_2 separation in industrial applications (Ge et al., 2024 [57]).

Ionic liquids, in particular, have demonstrated considerable potential in carbon capture systems by providing energy savings of 20-40% compared to traditional solvents. Their unique properties, including high thermal stability (up to 200°C) and low volatility, make them highly effective for long-term operations, ensuring reduced environmental impact and enhanced efficiency (Ab Rahim et al., 2023 [58]). The CESAR1 solvent system further exemplifies advancements in alternative solvents, offering improved resistance to degradation and operational longevity compared to conventional amines like MEA. However, challenges in industrial-scale adoption persist due to complexities in solvent handling and degradation management. As part of hybrid systems, CESAR1 could complement other novel materials, such as ionic liquids, leveraging its stability to enhance overall system performance (Morlando et al., 2024 [59]).

An example of non-amine carbon capture innovation within the UK is the Viridor Runcorn Carbon Capture Project, which utilises Shell's CANSOLV CO_2 capture technology. While primarily an advanced amine-based system, its adoption highlights the potential of alternative approaches to further enhance operational sustainability in large-scale industrial clusters like HyNet. Exploration of non-amine technologies, such as those discussed above, could complement existing solutions, offering scalable, energy-efficient alternatives to meet growing decarbonisation demands (Technip Energies, 2024 [60]; Viridor, 2024 [61]).

Choline-based deep eutectic solvents (DESs) also present a promising pathway, offering biodegradable and low-volatility solutions while reducing greenhouse gas emissions during solvent regeneration. Studies have shown that increased water content in DESs enhances CO_2 absorption kinetics, with choline chloride/glycerol-based DESs achieving optimal CO_2 solubility and absorption performance at 50 wt% water content and 293.15 K (Ciriaco et al., 2023 [62]). Similarly, enzyme immobilisation has emerged as a solvent-free alternative for carbon capture. Carbonic anhydrase enzymes embedded in porous silica or hydrogels have demonstrated over 90% activity retention across multiple cycles, providing an efficient and sustainable option for CO_2 capture (Ren et al., 2020 [63]).

Other innovative approaches include nonthermal plasma systems, which dissociate CO_2 into CO and O_2 at ambient conditions. When integrated with catalysts such as Ni/Al_2O_3, these systems have achieved conversion efficiencies of up to 41.14%, making them an attractive option for carbon capture and utilisation applications (Zaychenko et al., 2023 [64]). Additionally, biochar, derived from renewable feedstocks, contributes to circular economy principles by promoting soil health and sustainability while providing dual benefits in CO_2 absorption and agricultural applications.

Energy Savings and Environmental Benefits

Non-amine-based systems demonstrate substantial energy efficiency, with regeneration energy consumption reduced by up to 65% compared to conventional systems (Mao et al., 2024 [55]). These technologies also align with regulatory standards by minimising environmental toxicity and operational hazards, particularly in ionic liquid and biochar-based solutions. A study on DESs highlighted a significant reduction in viscosity as water content increased, from 520.8 mPa·s at 30 wt% to 15.72 mPa·s at 50 wt%, improving energy efficiency in CO_2 capture processes (Ciriaco et al., 2023 [62]).

The advancements in alternative solvents and materials underscore their potential to offer more efficient, environmentally friendly carbon capture solutions that extend beyond traditional amine-based systems. In industrial applications, silica-alkoxylated polyethyleneimine (SPEI)-based systems have shown substantial energy savings and environmental benefits over traditional amine systems. For instance, SPEI adsorbents used in cement plants require 33% less regeneration energy compared to MEA systems, with energy demands of 2.36 GJ/t CO_2 versus 3.53 GJ/t CO_2 for MEA.

Furthermore, lifecycle assessments reveal 7–26% lower impacts on human health, ecosystems, and resource depletion. Despite these advantages, SPEI systems remain underexplored at industrial scales, necessitating further research to validate their long-term feasibility in continuous operations (Jaffar et al., 2024 [65]).

Health and Environmental Implications of Carbon Capture

The health and environmental impacts of carbon capture technologies, particularly those employing amine-based solvents, have raised significant concerns due to the formation of degradation byproducts such as nitrosamines and nitramines. These byproducts, known for their carcinogenic and toxic properties, necessitate robust emission control systems and extensive environmental monitoring to mitigate associated risks. Nitrosamines, which exhibit acute toxicity and genotoxicity, degrade relatively quickly in aquatic environments, while nitramines are more persistent, increasing their risk of environmental accumulation (Gjernes et al., 2013 [66]).

In response to these concerns, Norwegian authorities have established temporary exposure thresholds of 0.3 ng/m^3 for air and 4 ng/L for drinking water to mitigate health risks (de Koeijer et al., 2013 [67]). Additionally, monitoring programs have revealed the accumulation of heat-stable salts (HSS) at levels reaching up to 0.5 wt% of MEA, highlighting the critical need for solvent management to minimise operational risks (Wagaarachchige et al., 2023 [33]). Toxicity assessments further highlight the potency of nitrosamines, with T25 values quantified at 0.075 mg/kg/day, emphasising the necessity for stringent emission controls (Gjernes et al., 2013 [66]). Mitigation strategies such as advanced demisters and ultraviolet (UV) treatment systems have proven effective, reducing secondary pollutant formation by up to an order of magnitude (de Koeijer et al., 2013 [67]).

Environmental studies have also revealed that meteorological factors significantly influence the dispersion of nitrosamines and nitramines. Dispersion models, such as CALPUFF and TAPM, demonstrate that stable atmospheric conditions during winter months can result in elevated concentrations of these byproducts near emission sources (Wu and Nelson, 2014 [68]). Wet deposition is identified as a primary mechanism for nitrosamine accumulation in aquatic systems, while nitramines exhibit extended stability in both soil and water (Yi et al., 2021 [69]). However, monitoring programs at facilities like Mongstad have shown that advanced mitigation measures effectively prevent significant accumulation, with no detectable levels of nitrosamines or nitramines in local water bodies (Gjernes et al., 2013 [66]).

Broader Climate Implications of Carbon Capture Technologies

Advanced emission control technologies, including Fourier Transform Infrared (FTIR) spectroscopy and gas chromatography, have significantly reduced nitrosamine and nitramine emissions to parts-per-billion levels, thereby minimising their secondary climate impacts (Cuccia et al., 2018 [70]). Additionally, sustainable utilisation pathways for captured CO_2, such as methanol production, have demonstrated a 95% reduction in greenhouse gas emissions compared to traditional methods (Peppas et al., 2023 [71]). The integration of renewable hydrogen into CO_2-to-methanol processes has further lowered lifecycle emissions to below 1.67 kg CO_2 eq/kg methanol, offering a scalable and sustainable approach to carbon management (Peppas et al., 2023 [71]). With global carbon dioxide emissions currently estimated at ~38,000 $MtCO_2$/year, achieving net-negative CO_2 emissions by 2050 remains a critical global objective. Carbon capture technologies, with capture efficiencies of ~98%, are indispensable in this transition to net zero and beyond (UK CCS, 2024 [72]).

To enhance the scalability and operational safety of post-combustion capture (PCC) facilities, several strategies have been implemented. Increasing stack heights and velocities, for instance, have proven effective in dispersion modelling, significantly reducing ground-level pollutant concentrations (Wu and Nelson, 2014 [68]). The development of alternative solvents, such as ionic liquids and DESs, also represents a promising avenue for achieving global carbon reduction targets. These non-amine-based solvents offer lower energy demands and reduced degradation risks, further improving their environmental and operational feasibility (Allangawi et al., 2023 [73]). This holistic approach underscores the critical role of innovative technologies and sustainable solutions in mitigating the broader health, environmental, and climate implications of carbon capture processes.

The HyNet Industrial Cluster is set to face increasing climatic pressures, including rising temperatures and shifting seasonal conditions. Temperature increases of up to 1.73°C (RCP5-8.5) are projected for 2040–2059, alongside drier summers and wetter winters, which pose direct challenges to carbon capture efficiency (Environment Agency, 2024 [1]). Elevated ambient temperatures accelerate solvent degradation, reducing CO_2 absorption capacity, while colder conditions slow reaction kinetics, further compromising efficiency. An et al. (2022) [74] demonstrated that under optimal conditions—temperatures above 17°C and high humidity—capture rates of 85% can be achieved, but these rates drop significantly under less favourable conditions, such as colder, drier weather (Environment Agency, 2024 [1]). This highlights the critical importance of advanced solvent technologies, including ionic liquids and metal-organic frameworks (MOFs), which maintain high capture efficiency across wide temperature ranges (Wilberforce et al., 2021 [75]; Allangawi et al., 2023 [73]).

Seasonal variations further affect capture efficiency. Humid summers in the HyNet region may enhance absorption rates for certain solvents but also elevate the risk of solvent degradation, while colder and drier winters can slow reaction kinetics and decrease overall capture rates (An et al., 2022 [74]; Environment Agency, 2024 [1]). For instance, high humidity combined with rising temperatures during summer months can intensify operational challenges, requiring advanced monitoring and optimisation strategies to maintain efficiency. Conversely, the lower temperatures in winter increase energy demands for solvent regeneration, creating an operational trade-off. Emerging hybrid ionic liquid-DES systems and temperature-resilient MOF adsorbents offer potential solutions by mitigating the efficiency losses associated with these climatic extremes (Wilberforce et al., 2021 [75]; Allangawi et al., 2023 [73]).

Water availability, integral to solvent-based systems, is another factor influenced by climate variability. Projected drier summers in the HyNet region may limit water availability for cooling and solvent regeneration, potentially lowering capture efficiency. Conversely, wetter winters can lead to higher operational costs associated with managing increased moisture and humidity (Environment Agency, 2024 [1]). To address these challenges, the integration of water-efficient technologies, such as wastewater recycling and renewable hydrogen inputs for solvent regeneration, offers a sustainable path forward (Peppas et al., 2023 [71]). With advanced environmental monitoring and adaptive operational strategies, the HyNet cluster can safeguard capture efficiency against the dual pressures of rising temperatures and seasonal variability.

Challenges, Gaps and Future Research

The deployment of amine-based carbon capture systems and hydrogen as a low-carbon energy carrier presents a range of challenges that require urgent attention, particularly in light of emerging research and technological advancements. These challenges span operational, environmental, and regulatory dimensions, with significant implications for the effectiveness and safety of these technologies.

In amine-based carbon capture systems, the degradation of solvents and the subsequent formation of harmful byproducts, such as nitrosamines and nitramines, remain a pressing concern. Studies have revealed that nitrosamine emissions in industrial settings can surpass safety thresholds of 0.3 ng/m³ for air and 4 ng/L for water, posing risks to human health and ecosystems (Gjernes et al., 2013 [66]; Låg, 2011 [76]). The study by Hamed et al. (2023) [54] highlights significant operational challenges in using amine solvents like monoethanolamine (MEA) in steam methane reforming (SMR) processes for carbon capture.

While MEA demonstrates high reactivity and CO_2 capture efficiency, it is also highly corrosive and imposes substantial regeneration energy costs, which can limit its scalability in industrial applications. Chemical absorption technologies like MEA-based systems have high energy consumption during solvent regeneration and are prone to degradation, which increases operational costs and reduces capture efficiency (Liu et al., 2023 [77]).

Advanced monitoring technologies, including PTR-MS and FTIR, have demonstrated exceptional sensitivity, with PTR-MS achieving detection limits as low as 0.02 µM for nitrosamines (Ullah et al., 2024 [36]). However, the high resource and maintenance requirements of these systems pose a barrier to widespread implementation, especially when scaled to industrial operations. The integrated CO_2 capture and hydrogenation process described in this study circumvents the energy-intensive desorption step by directly converting captured CO_2 into formate, a liquid hydrogen carrier. However, the requirement for precise catalyst characterisation and optimisation, such as the utilisation of Pd/NAC catalysts with specific particle sizes (e.g., 2.8 ± 0.2 nm) for high catalytic activity, indicates a significant operational complexity that limits scalability and cost-effectiveness for industrial applications (Li et al., 2022 [46]). Additionally, the observed dependency of formate yield on CO_2 loading levels, with an optimal yield of 82.6% achieved at 0.3 mol CO_2/mol TEA, underscores the need for stringent operational control to maximise efficiency. A recent study highlighted that amine degradation could release up to 1.2 g of ammonia per kilogram of solvent processed under suboptimal operational conditions, complicating efforts to mitigate secondary emissions (Wagaarachchige et al., 2024 [78]).

Suboptimal conditions, such as temperature extremes and gas composition variability, present significant challenges to the performance of amine-based carbon capture systems. Wagaarachchige et al. (2024) [78] demonstrated that operating temperatures exceeding 160°C during thermal reclaiming cycles accelerate solvent degradation, leading to the formation of heat-stable salts (HSS) that reduce CO_2 absorption efficiency. Similarly, gas streams containing impurities exacerbate solvent degradation and increase the formation of corrosive byproducts, such as ammonia and nitrosamines.

These conditions highlight the importance of maintaining optimal operational parameters to mitigate performance losses. Real-time monitoring technologies, such as Fourier-transform infrared (FTIR) spectroscopy, combined with advanced chemometric tools like partial least squares regression (PLS-R), have proven effective in detecting early signs of solvent degradation. By identifying these issues in real-time, operators can implement timely interventions, such as adjusting reclaiming cycles or improving gas pre-treatment processes, to prevent long-term performance declines (Wagaarachchige et al., 2024) [78].

Hamed et al. (2023) [54] reports that MEA achieves CO_2 capture rates of up to 99% in shifted gas streams under optimal conditions. However, this efficiency drops to 70% in flue gas streams due to lower partial pressures of CO_2 and challenges associated with maintaining consistent reaction kinetics across diverse gas compositions. These discrepancies highlight the need for customised process designs to optimise solvent performance across different gas streams.

In addition to monitoring challenges, the operational stability of equipment exposed to corrosive byproducts is a major concern. Continuous exposure to degraded amines and flue gases accelerates wear and tear, with maintenance costs in industrial facilities increasing by as much as 25% over the past five years (Neerup et al., 2023 [37]). Recent advancements in the development of oxidation-resistant adsorbents, such as cyclodextrin-based metal-organic frameworks (CD-MOFs), highlight the limitations of current sorbents in withstanding high oxygen partial pressures present in emissions.

For example, the study demonstrates that KHCO3 CD-MOF possesses significant thermal and oxidative stability while achieving high CO_2 adsorption capacities (2.50 mmol/g at 1 bar CO_2 and 40 °C). This material shows potential for reversible CO_2 capture under realistic flue gas conditions, outperforming traditional amine-based systems in terms of oxidative stability. However, challenges such as reduced CO_2 capacities under humid conditions remain unresolved, as the hydrophilic pore environment hinders adsorption efficiency.

These findings underscore the urgent need for alternative sorbents capable of balancing oxidative resilience with operational efficiency under various environmental conditions (Zick et al., 2022 [56]). The scalability of promising materials like ionic liquids and metal-organic frameworks (MOFs) is hindered by high production costs and environmental concerns associated with their synthesis, restricting their application beyond laboratory settings (Liu et al., 2023 [77]).

While advanced materials have been proposed for improving durability, the costs associated with retrofitting existing facilities remain prohibitive for many operators. The absence of harmonised reference standards for amine monitoring further exacerbates these challenges, with European guidelines such as EN 15259 and EN 13284 failing to account for the specific needs of amine-based systems (Jarvinen et al., 2012 [42]). Membrane technologies for CO_2 capture face scalability challenges due to maintaining high selectivity and permeability in mixed matrix membranes, which are often compromised by poor compatibility and material defects (Liu et al., 2023 [77]).

For hydrogen technologies, the risk of leakage presents a critical challenge, given hydrogen's small molecular size and high diffusivity. The transition to a hydrogen-based economy faces significant obstacles, including energy inefficiencies throughout the supply chain. Current estimates show that approximately 30-35% of energy is lost during hydrogen production through electrolysis, 13-25% is lost in liquefaction or conversion to carriers such as ammonia, and another 10-12% is lost during transportation. Additionally, fuel cell applications result in an additional 40-50% energy loss, cumulatively requiring significant renewable energy input to make hydrogen competitive with direct electrification approaches (Agarwal, 2022 [79]).

Leakage rates of 1–10% have been reported across various stages of the hydrogen supply chain, with even a 1% leakage rate contributing an additional 0.03°C of global temperature rise by 2050. A 10% leakage rate could raise this figure to 0.27°C, significantly offsetting the climate benefits of transitioning to hydrogen systems (Ocko and Hamburg, 2022 [23]). CO_2 storage in geological formations like saline aquifers poses risks due to potential leakage and reservoir integrity issues, with long-term monitoring and mitigation strategies still underdeveloped (Liu et al., 2023 [77]).

Hydrogen leakage from subsurface storage presents both subsurface and surface challenges, requiring advanced monitoring and mitigation strategies. Despite its potential, blue hydrogen faces significant challenges, particularly its reliance on natural gas and carbon capture inefficiencies. Studies reveal real-world capture rates of 70%-85%, falling short of the 95% benchmark required for climate-friendly hydrogen. Additionally, methane leakage rates between 1%-4% amplify its carbon footprint. In contrast, green hydrogen shows promise, driven by falling electrolyser costs and technological advancements that enhance scalability. These findings highlight the urgent need for harmonized regulatory frameworks to prioritize low-impact production methods and robust monitoring systems for leakage across the hydrogen value chain (Schlissel and Juhn, 2023 [19]; Pasimeni et al., 2022 [80]).

Leakage pathways in geological formations can include caprock fractures, faults, and compromised wellbores, making it difficult to identify all potential escape routes. Additionally, hydrogen's interaction with groundwater can lead to contamination risks, as subsurface hydrogen may react with minerals and microbial communities, producing byproducts such as hydrogen sulphide (H_2S).

At the surface, undetected hydrogen migration can result in emissions that not only compromise the energy efficiency of storage systems but also pose flammability hazards. Recent advancements in subsurface monitoring, including pressure and temperature sensors, tracer gas injection techniques, and real-time surface detection systems, have improved the ability to identify and mitigate hydrogen leakage. However, the deployment of such technologies remains limited due to cost and technical barriers, necessitating further research and development to ensure the safety and reliability of underground hydrogen storage (Goodman et al., 2024 [81]; NETL, 2022 [82]).

Hydrogen’s indirect greenhouse gas effects are particularly concerning; it can extend methane lifetimes by 15–20% and contribute to ozone formation, with radiative forcing impacts 200 times greater than CO_2 on a per-mass basis in the short term (Alsulaiman, 2024 [83]). These findings denote the importance of stringent containment and detection strategies. The need for harmonised regulatory frameworks to enable international hydrogen trade is another pressing challenge.

Currently, discrepancies in defining 'low carbon' hydrogen among nations hinder global market formation. Establishing uniform certification schemes such as 'Guarantee of Origin' systems and robust Measurement, Reporting, and Verification (MRV) techniques will be critical for scaling hydrogen adoption on a global scale (Agarwal, 2022 [79]). Recent advancements, such as hydrogen-compatible alloys for pipelines and real-time detection sensors, have demonstrated the potential to reduce leakage by up to 70%, though widespread adoption remains hindered by cost and infrastructure limitations (Wei et al., 2024 [16]).

Environmental and safety challenges associated with hydrogen storage are also increasingly evident. Simulations using liquid helium as a proxy for hydrogen have demonstrated that leaks disperse up to 1.5 times faster in high-wind conditions, complicating containment efforts in exposed storage facilities (Shu et al., 2022 [26]). Furthermore, smaller liquid hydrogen tanks, which are often used for mobility applications, experience rapid pressure build-up due to higher surface-to-volume ratios, resulting in boil-off losses exceeding 15% in suboptimal conditions (Matveev and Leachman, 2023 [27]). Strategies such as enhanced insulation and active venting systems have mitigated these losses in experimental setups, but their scalability and economic feasibility remain unclear.

The health impacts of hydrogen and amine systems further amplify these concerns. Hydrogen leaks, while not toxic themselves, indirectly exacerbate air quality issues by increasing tropospheric ozone concentrations. Similarly, the carcinogenic properties of nitrosamines necessitate stringent monitoring. Toxicity assessments reveal T25 values of 0.075 mg/kg/day for nitrosamines, highlighting their significant health risks (Gjernes et al., 2013 [66]). Advanced mitigation measures, such as UV treatment and catalytic converters, have been shown to reduce nitrosamine emissions by up to 90%, but their adoption has been inconsistent across facilities due to high installation costs (de Koeijer et al., 2013 [67]).

The permitting of these technologies in the UK presents challenges for progression, due to uncertainties in process chemistry, emissions and air quality impacts on human health and ecological sites. Currently, amine emissions permits are calculated based on declared achievable emissions provided by manufacturers and modelled impacts which provide an acceptable risk to human health and ecological receptors. These are based on maximum allowable emissions and represent worst-case scenarios due to the large uncertainties in the process. The FuNitr collaborative project led by NIVA in Norway is working to improve this method and increase knowledge to reduce the uncertainties within the process and produce a tool to increase guidance on this methodology (NIVA, 2023 [84]). The lack of information in this area is a limit to permit applications for carbon capture and could become a constraint for future developments accounting for cumulative impacts. Therefore, increased knowledge of these uncertainties will support the permitting process.

Finally, regulatory frameworks for both hydrogen and amine technologies are lagging behind technological advancements. The relatively high cost of low-carbon hydrogen production further impedes scalability. For instance, the levelised cost (the average cost of generating electricity over a power plant's lifetime) of green hydrogen remains higher than that of grey or blue hydrogen due to the elevated capital expenditure for electrolysers and renewable energy inputs. Despite decreasing costs of electrolysis and renewable energy, significant disparities in infrastructure readiness and market demand exacerbate these challenges. Strategic policies like tax credits or mandates for hydrogen use in industrial sectors can help bridge this gap (Agarwal, 2022 [79]).

The lack of international consensus on permissible emission thresholds and leakage rates undermines efforts to standardise monitoring and mitigation practices. For example, while European standards address general air quality concerns, they fail to incorporate the specific risks posed by nitrosamines and hydrogen leakage (Jarvinen et al., 2012 [42]). A coordinated effort involving policymakers, researchers, and industry stakeholders is essential to establish harmonised guidelines that address these emerging challenges comprehensively.

These challenges denote the need for continued investment in research and development to advance both the technical and regulatory dimensions of carbon capture and hydrogen technologies. Addressing these issues is critical to realising the potential of these systems as cornerstones of a sustainable, low-carbon future.

Conclusions and Recommendations

The findings of this literature review underscore the transformative potential of both amine-based carbon capture systems and hydrogen technologies in advancing decarbonisation efforts across industries, transportation, and energy systems. Amine-based carbon capture systems have demonstrated significant advancements, particularly in monitoring technologies and solvent innovations. Real-time detection techniques have improved the identification and management of harmful byproducts such as nitrosamines and nitramines, reducing the environmental and health risks associated with solvent degradation. Additionally, innovations in solvent systems, including hybrid and biphasic configurations, have successfully reduced energy demands while maintaining high CO_2 capture efficiencies. However, operational challenges persist, including high regeneration energy requirements, equipment durability issues, and a lack of standardised monitoring protocols. These limitations necessitate continued research and development, particularly in areas such as advanced solvents, alternative capture methods, and scalable monitoring solutions.

Hydrogen technologies emerge as a cornerstone of the low-carbon energy transition, with applications spanning power generation, industrial decarbonisation, and transportation. Their versatility and zero-carbon combustion profile make them an attractive alternative to fossil fuels. However, hydrogen's high diffusivity and propensity for leakage pose significant challenges, particularly given its indirect greenhouse gas effects, which can amplify methane lifetimes and increase tropospheric ozone levels. While innovations such as hydrogen-compatible materials and real-time detection systems show promise in mitigating these risks, challenges related to cost, scalability, and infrastructure readiness persist. Additionally, hydrogen's use in subsurface storage introduces complexities, including the difficulty of identifying all potential leakage pathways, the risks of groundwater contamination, and flammability hazards from surface emissions. Addressing these issues requires integrated monitoring frameworks and advanced containment strategies, coupled with harmonised international standards to guide implementation.

Non-amine solvents, such as ionic liquids and deep eutectic solvents, demonstrate significant potential for reducing energy demands and environmental impacts. However, these alternatives have not yet been extensively tested in large-scale projects or for long-term operational feasibility, which limits their immediate scalability. Further pilot projects and industrial-scale testing are critical to validate their effectiveness and optimise their application within the decarbonisation framework. In the HyNet region, the exploration of these alternatives could complement ongoing hydrogen and carbon capture efforts, providing an opportunity to enhance the sustainability and efficiency of the cluster's decarbonisation strategies.

The HyNet Industrial Cluster serves as a prime example of how integrated hydrogen and carbon capture systems can advance regional decarbonisation goals. With its salt cavern storage facility, hydrogen production at the Stanlow Manufacturing Complex, and the extensive Cadent pipeline, HyNet demonstrates the feasibility of building a hydrogen economy supported by carbon capture and storage technologies. Additionally, hydrogen's role in HyNet highlights the importance of robust infrastructure to manage leakage risks and maintain the cluster's contribution to broader climate goals. The integration of advanced sealing technologies and real-time monitoring systems within HyNet's pipelines and storage facilities is a model for addressing operational and environmental challenges.

A key knowledge gap exists in understanding the long-term environmental and operational impacts of both amine-based carbon capture systems and hydrogen technologies. For amine-based systems, the accumulation of degradation byproducts, the variability in emissions under different operational conditions, and the lack of harmonised methodologies for emissions monitoring and control represent critical areas for further study. Similarly, hydrogen technologies require deeper exploration into their indirect climate effects, the risks associated with subsurface storage, and the performance of advanced materials under real-world conditions. These gaps highlight the need for sustained investment in both research and pilot projects to validate and optimise emerging solutions.

To address these challenges, a coordinated approach is needed that brings together policymakers, researchers, and industry stakeholders. Investment in advanced materials and technologies that enhance the durability, efficiency, and safety of amine-based systems is critical. The adoption of innovative solvents and materials, such as ionic liquids, deep eutectic solvents, and enzyme-based alternatives, can reduce energy demands and mitigate environmental risks. For hydrogen technologies, prioritising the development of leakage detection systems, hydrogen-compatible pipelines, and advanced sealing technologies will enhance safety and efficiency. Policies should incentivise the adoption of these technologies through tax credits, grants, and other financial mechanisms, ensuring that both carbon capture and hydrogen infrastructure are deployed at scale.

While amine-based carbon capture systems and hydrogen technologies hold immense potential, their widespread deployment will depend on overcoming significant technical, operational, and regulatory challenges. By addressing these gaps through research, innovation, and collaboration, these technologies can play a pivotal role in achieving a sustainable, low-carbon future. The HyNet Industrial Cluster exemplifies how targeted investments in infrastructure and innovative technologies can serve as a blueprint for other regions aiming to decarbonise on a large scale. A balanced approach that integrates technological advancements with policy support and environmental stewardship will be crucial in realising their full potential.

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