Environmental Capacity in Industrial Clusters

Phase 4: Air Quality in HyNet

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1. Executive Summary

The Department for Energy Security and Net Zero (DESNZ) has continued to sponsor the Environment Agency (EA) to investigate and report on the environmental capacity to deploy carbon capture and hydrogen production technologies in key English industrial clusters. Launched in 2021, this work aims to support UK Government's Net Zero Strategy and the ambition to become a clean energy superpower, addressing key environmental capacity challenges while enabling the sustainable growth of low carbon industrial clusters in line with the Government's growth agenda. As the environmental regulator in England, the EA plays a vital role in enabling the development of industrial clusters to meet emissions targets and safeguard the environment through regulation and advisory roles.

This report specifically assesses the air quality impacts associated with low carbon technology deployment on permitted installations in the English portion of the HyNet industrial cluster and associated regulatory challenges. The assessment reflects the project's funding arrangement and stakeholder engagement, focusing on England. Environmental matters in Wales are devolved to Welsh Ministers and are not within the scope of this study. It focuses on emissions from hydrogen production, hydrogen combustion and carbon capture processes, as well as the cumulative nitrogen deposition impacts on sensitive ecological receptors. Infrastructure beyond industrial installations is not within the scope of this study, however, all infrastructure would be subject to the same considerations in terms of emissions to air.

Image: View north-west towards the HyNet area and Ellesmere Port. Image captured by the EA for use in this Project.

The approach taken in this phase extends previous work to explore the state of the environment, industry plans and the capacity of the environment to support low carbon technology deployment. Stakeholder engagement has been developed from lessons learned in Phases 1-3, with expanded engagement with industry representatives, regulatory bodies and trade associations.

Previous phases of this work have explored environmental capacity challenges across various industrial clusters. Phase 1 (2021-2022) considered water availability and water quality in the Humber industrial cluster. Phase 2 (2022-2023) expanded the focus to consider air quality and flood risk in Humber and water availability and water quality in the Teesside industrial cluster. Phase 3 (2023-2024) examined air quality impacts in Teesside and considered water availability and quality in HyNet. Phase 4 (2024-2025) focuses on air quality within the HyNet industrial cluster, using baseline analysis and stakeholder engagement to understand existing and potential future air quality impacts. In addition to this report, Phase 4 also includes work on strategic spatial planning (SSP) to support industrial decarbonisation and a final Executive Summary, which consolidates the key findings from the four-year programme. These are available separately.

Findings from Phase 3 (2023-2024) highlighted key air quality challenges for the Teesside industrial cluster where emissions from low carbon technology presented regulatory and environmental concerns. The study identified concerns for nitrogen deposition, hydrogen-related nitrogen oxides (NO_x) emissions and the formation of amine degradation products from carbon capture processes. It also emphasised the need to expand and enhance air quality monitoring and provide regulatory clarity to address cumulative impacts on sensitive ecological sites. Work in Phase 4 builds on these findings by further investigating air quality risks within the HyNet industrial cluster and evaluating the potential for mitigation strategies to support sustainable low carbon industrial development.

Understanding the potential for air quality impacts plays a critically important role in the sustainable delivery of a net zero future. The deployment of low carbon technology is already contributing to significant reductions in carbon dioxide (CO_2) and sulphur dioxide (SO_2) emissions, but continued assessment is needed to ensure that new pollutants, such as NO_x and amine degradation products, are effectively managed. Both amines and their degradation byproducts, including nitrosamines and nitramines, are of concern. While amines are likely present in higher concentrations, degradation products are more hazardous and can also form post-release in the atmosphere. Air quality must continue to improve and not be compromised by new and emerging technologies aimed at reducing CO_2 emissions.

The HyNet industrial cluster is a significant decarbonisation initiative in North West England and North West Wales, integrating low carbon hydrogen production, carbon capture and storage (CCS) and industrial emission reduction strategies. Existing air pollution in the region, combined with new emission sources from low carbon technology, present challenges that must be managed to ensure environmental compliance and public health protection.

The HyNet industrial cluster experiences cumulative nitrogen and sulphur deposition from multiple sources, including industry, transport and agricultural activities. Critical loads for nitrogen deposition are exceeded in some ecological receptors, raising concerns about cumulative environmental impacts. Industrial emissions, particularly sulphur and nitrogen deposition, contribute significantly to air quality concerns. Sensitive ecological sites such as Holcroft Moss Site of Special Scientific Interest (SSSI), part of the Manchester Mosses Special Area of Conservation (SAC), are particularly vulnerable due to in-combination impacts.

This report does not assess ecological sensitivities of protected sites in Wales within the HyNet area, as they fall outside the project scope. Strategic mitigation measures, including additional air quality assessments and restoration strategies, have been proposed to address these risks.

Image: Intergen CCGT Power Plant, Runcorn with a view over Cheshire in the background. Intergen will be supplied with blue hydrogen from HyNet main and will operate on a mix of natural gas/hydrogen. Image supplied by Progressive Energy.

The main findings of this review of Air Quality in HyNet within Phase 4 are:

1. Air quality risks from hydrogen production and use require stronger regulatory oversight

While hydrogen plays a critical role in industrial decarbonisation, its combustion introduces NO_x emissions, which require careful regulation. Environmental Assessment Levels (EALs) for NO_x have been well established through recent EA work (Environment Agency – The Environmental Protection, 2024; Environment Agency – Medium Combustion Plant: Emission Limit Values, 2024). However, regulatory challenges remain regarding the application of control technologies for hydrogen combustion, particularly for smaller Medium Combustion Plant Directive (MCPD) units and hydrogen blends in natural gas pipelines. Currently, some hydrogen combustion applications may lack established emission control requirements, such as Selective Catalytic Reduction (SCR) or Selective Non-Catalytic Reduction (SNCR), which are standard for larger combustion plants. Addressing these technology-specific regulatory gaps will be necessary to ensure that hydrogen combustion does not result in unintended air quality impacts.

2. Hydrogen leakage requires greater monitoring and risk assessment

Stakeholders identified hydrogen leakage as both an industrial and regulatory challenge, with potential climate and safety implications. While hydrogen itself is not a direct greenhouse gas, its interaction with atmospheric methane and ozone contributes to indirect global warming effects. Small-scale leaks from pipelines, storage and industrial processes could also present safety risks and undermine public confidence in hydrogen deployment. Strengthening detection, monitoring and reporting frameworks for hydrogen emissions is essential to mitigating these risks.

3. Carbon capture must address secondary emissions and advance non-amine solvent research

Amine-based carbon capture is currently the dominant technology, but concerns remain over the formation of nitrosamines and nitramines, which require improved monitoring frameworks and regulatory adaptation. Phase 4 reinforces the need to progress research into alternative, non-amine-based solvents, such as ionic liquids and metal-organic frameworks (MOFs), to reduce secondary emissions and improve capture efficiency. Encouraging pilot studies on non-amine carbon capture technologies could support the transition to lower-impact CCS solutions that align with evolving regulatory and environmental standards.

4. Baseline air quality monitoring and cumulative impact assessments need strengthening

The HyNet industrial cluster includes sensitive ecological sites, such as the Mersey Estuary SPA and Holcroft Moss SSSI within the Manchester Mosses SAC, which are already exceeding critical nitrogen deposition loads. However, current air quality monitoring does not adequately track key pollutants, including NO_x, ammonia (NH_3), amine degradation products and hydrogen emissions. Strengthening regional ambient air quality monitoring networks is critical for cumulative impact assessments, ensuring that regulatory frameworks effectively manage the long-term effects of industrial expansion while protecting ecological receptors.

While individual air quality assessments may indicate that specific projects remain within compliance thresholds, the cumulative impact of emissions from multiple industrial sources presents regulatory and permitting challenges. The Holcroft Moss Habitat Mitigation Plan proposes funding contributions from developments to support ecosystem resilience and offset nitrogen deposition risks. Despite national reductions in NO_x and NH_3 emissions since 2005, ongoing industrial expansion within HyNet may elevate nitrogen emissions, potentially affecting biodiversity, soil health and ecological integrity. Strengthened long-term monitoring and adaptive regulatory frameworks will be essential to balancing industrial growth with environmental sustainability.

Future research should focus on refining cumulative impact assessments, advancing hydrogen and CCS deployment strategies and enhancing stakeholder engagement to secure the long-term viability of industrial decarbonisation in the HyNet region.

2. Background

Low carbon technology is fundamental to achieving net zero and mitigating climate change. Their deployment is essential to reducing greenhouse gas emissions, but they also introduce new environmental and regulatory challenges. Carbon capture and hydrogen production and use present potential risks to air quality, public health and ecological receptors. These risks must be carefully managed to ensure that the transition to low carbon industry does not compromise environmental integrity or regulatory compliance. Understanding the cumulative impacts of these technologies is vital for ensuring their sustainable deployment in industrial clusters.

The focus of the Phase 4 study is air quality in the HyNet industrial cluster, a major decarbonisation initiative in North West England and North Wales integrating hydrogen production, CCS and industrial emission reduction strategies. The cluster aims to support national net zero targets while maintaining industrial competitiveness. However, the introduction of new emission sources from hydrogen combustion and CCS infrastructure, in combination with existing industrial and transport-related emissions, presents challenges for air quality management. A robust understanding of these impacts is necessary to support informed decision-making, regulatory compliance and environmental permitting.

Image: Green Energy Production adjacent to the Manchester Ship Canal with the Protos Site in the background. Image captured by the EA for use in this Project.

Industrial clusters such as HyNet host a diverse range of sectors, including heavy industries, power generation and chemical manufacturing, each with distinct environmental footprints. Large-scale proposals for hydrogen production and CCS are expected to contribute significantly to emissions reductions, but they must also navigate stringent environmental requirements. Regulatory bodies need to assess how these developments will interact with existing pollution sources and ensure that their impacts are effectively mitigated through permitting and environmental management strategies. The integration of hydrogen and CCS into industrial operations will require updated emission limit values (ELVs), improved monitoring frameworks and coordinated mitigation efforts to prevent adverse effects on air quality.

The deployment of hydrogen production technologies introduces key air quality considerations. Hydrogen combustion can generate elevated levels of NO_x, necessitating advanced burner designs and emissions control measures to prevent exceedances of air quality standards. Additionally, the risk of hydrogen leakage during production, transportation and storage could have climate implications, as hydrogen can influence atmospheric chemistry and prolong the lifetime of methane, a potent greenhouse gas. Further research and monitoring will be needed to quantify these effects and implement effective leakage control measures.

Carbon capture technologies, particularly those relying on amine-based solvents, also raise environmental concerns. Amine degradation products, including nitrosamines and nitramines, have potential human health and ecological risks. Existing regulatory frameworks require enhanced monitoring and assessment of these byproducts to ensure compliance with environmental standards. Alternative non-amine CCS solvents, such as ionic liquids and metal-organic frameworks, have been identified as potential options for reducing emissions and energy penalties. However, research into their large-scale feasibility appears limited, with amine-based solvents remaining the dominant focus of carbon capture development.

Environmental risks associated with industrial expansion in HyNet extend to sensitive ecological sites, which are already experiencing elevated nitrogen deposition from industrial, agricultural and transport-related sources. Holcroft Moss, part of the Manchester Mosses SAC, is particularly vulnerable to cumulative nitrogen and sulphur deposition, raising concerns about long-term biodiversity impacts. Strategic mitigation measures, including cumulative impact assessments and habitat restoration initiatives, are essential to address these risks.

This phase builds upon previous investigations into environmental capacity within industrial clusters, focusing on air quality challenges in the HyNet industrial cluster. It extends the evidence base through baseline environmental assessments, regulatory evaluations and stakeholder engagement to ensure that the deployment of low carbon technology aligns with environmental sustainability and public health objectives. Additionally, this phase includes a review of SSP and a final executive summary consolidating findings from the four-year work.

2.1. Project Objectives

This work aims to support the UK Government's Net Zero Strategy and Clean Growth Agenda by facilitating the environmentally sustainable development of low carbon industrial clusters. In line with the Government's ambition to become a clean energy superpower and achieve up to 10GW of low carbon hydrogen production by 2030 (Labour Party, 2024), this phase extends the project to include an air quality-focused assessment of the HyNet industrial cluster. Through this work, the EA can further identify environmental limits and regulatory challenges associated with hydrogen production and carbon capture deployment, ensuring that industrial decarbonisation aligns with national climate goals (HM Government, 2024). Additionally, this research informs Defra's approach to addressing environmental capacity challenges, helping to refine regulatory frameworks, mitigate environmental risks and reduce delays in technology deployment (HM Government, 2022).

One aim of this project is that all industrial clusters proactively assess their environmental challenges before designing and deploying low carbon technology. Early identification and mitigation of potential impacts will benefit the permitting and planning processes, improve regulatory compliance and ensure that industrial decarbonisation aligns with environmental protection objectives. This will also aid industry to secure investment and infrastructure support by reducing uncertainties associated with environmental regulations.

The objectives for Phase 4 of this project were to:

- **Develop an improved evidence base** on the air quality impacts of low carbon technology within the HyNet industrial cluster, particularly the effects of hydrogen production, combustion emissions and carbon capture solvents on regional air quality and ecological receptors.
- **Assess the cumulative impact of industrial emissions** by integrating baseline air quality data with projected emissions from hydrogen and CCS projects. This includes evaluating potential exceedances of NO_x, NH_3 and amine degradation products, as well as ensuring that regulatory frameworks account for interactions between multiple pollutant sources. Further refinement of modelling techniques and monitoring strategies is needed to improve cumulative impact assessments.
- **Investigate the environmental and regulatory challenges** posed by hydrogen leakage, including its potential indirect greenhouse gas effects through interactions with atmospheric methane and tropospheric ozone formation.
- **Evaluate technological and regulatory responses** to amine-based carbon capture emissions, including monitoring advancements, degradation risks from nitrosamines and nitramines and alternative non-amine solvents such as ionic liquids and MOFs.

- **Strengthen stakeholder engagement** by expanding collaboration with regulatory bodies (such as the UK Health Security Agency and Natural England), industry groups and local authorities to facilitate knowledge exchange on air quality management and regulatory pathways.
- **Examine mitigation strategies for sensitive ecological sites** affected by cumulative nitrogen and sulphur deposition, including targeted restoration funding mechanisms and enhanced air quality monitoring networks.
- **Support strategic decision-making for sustainable industrial development** by providing regulatory bodies, industry and policymakers with insights into air quality constraints and feasible emission reduction measures in the HyNet region.

Phase 4 focuses primarily on the air quality impacts in HyNet, aligning with the project's progression toward a comprehensive environmental assessment framework for low carbon industrial development.

These insights, along with strategic recommendations, are captured in an overarching Executive Summary, which accompanies this and previous reports. Additionally, the findings contribute to the broader SSP review, supporting evidence-based policy and regulatory development for the UK's industrial transition to net zero.

Image: Encirc, Elton, Chester and view down River Mersey in the background. Encirc is proposing to operate its boilers using hydrogen. Image supplied by Progressive Energy.

2.2. Role of the Environment Agency

The EA plays a pivotal role in regulating industrial emissions and supporting the UK's transition to net zero. By enforcing environmental standards and overseeing carbon markets under the UK Emissions Trading Scheme, the EA ensures that low carbon industrial developments, including hydrogen production and carbon capture, align with national decarbonisation goals while maintaining air, water and ecological quality.

Within industrial clusters, the EA regulates emissions under the Environmental Permitting Regulations (EPR), covering pollutants such as NO_x, sulphur compounds, NH_3 and volatile organic compounds (VOCs). It also works alongside the Health and Safety Executive (HSE) as a competent authority under the Control of Major Accident Hazards (COMAH) Regulations, ensuring the safe storage and handling of hydrogen and CO_2 in large-scale infrastructure projects, such as underground hydrogen storage (UHS) and CCS facilities.

Beyond regulation, the EA provides guidance to Local Planning Authorities (LPAs), industry and policymakers, helping to integrate sustainability considerations into new industrial developments. This includes addressing water resource constraints, flood risks and cumulative air quality impacts to ensure that decarbonisation does not lead to unintended environmental consequences. The EA is also actively involved in research collaborations to refine impact assessments, advance emissions monitoring techniques and has developed guidance on emerging techniques (GET) for hydrogen and CCS deployment.

To facilitate industry's decarbonisation readiness, the EA is working with stakeholders to refine permitting pathways, improve emissions monitoring frameworks and address emerging regulatory challenges, such as hydrogen leakage, NO_x emissions and amine degradation products from CCS. As industrial clusters scale up low carbon technologies, the EA's role in enabling regulatory clarity and ensuring that environmental safeguards keep pace with innovation remains crucial. In line with its statutory Growth Duty under the Deregulation Act 2015 (HM Government, 2024), the EA also seeks to support sustainable economic growth by ensuring that regulation is proportionate, enabling businesses to innovate while maintaining high environmental standards.

3. Project Methodology

3.1. Overview

The Phase 4 project team was made up of national and local area EA staff. Members of the project team had experience in climate change adaptation and mitigation, communications and engagement, regulated industry and project management. The project team also worked in consultation with additional internal experts in water resources, water quality, air quality and climate change. External consultants supported the project team to draw the evidence together, conduct a literature review, support the stakeholder engagement exercise and develop the final products. This informed the anticipated needs and environmental capacity of deploying low carbon technology directly from stakeholder groups.

3.2. Literature Review and Evidence Baseline

The Phase 3 literature review for the air quality in Teesside explored the environmental and technological implications of hydrogen as a sustainable fuel and carbon capture technologies, assessing applications such as NH_3 cracking, hydrogen combustion and its role in industrial plants. It highlighted key environmental challenges, including hydrogen leakage and emissions from amine-based carbon capture, particularly nitrosamines and nitramines and identified gaps in understanding their ecological and air quality effects. The review also emphasised the need for robust monitoring strategies for emerging technologies. Building on these findings, the Phase 4 review of air quality in HyNet aims to advance knowledge on recent developments in amine-based carbon capture and hydrogen technologies, focusing on improved monitoring techniques, solvent innovations and strategies to mitigate environmental and health risks.

The literature review of air quality conducted for HyNet focused on key environmental and technical considerations associated with low carbon technology, particularly hydrogen production, storage and carbon capture. The review assessed advancements in amine-based carbon capture systems, including monitoring techniques, degradation risks and emerging alternatives. Additionally, it explored hydrogen’s combustion characteristics, its role in decarbonising energy-intensive sectors and the environmental implications of hydrogen leakage. The broader health and ecological risks associated with these technologies were also considered, particularly in relation to nitrogen deposition, air quality and long-term regulatory challenges. A more detailed breakdown of the literature review methodology, including the specific assessment criteria and key themes, is provided in the Literature Review for air quality in HyNet (Environment Agency Phase 4 Annex 1, 2025).

The literature review followed a structured methodology, using predefined search terms across academic and industry databases, including Scopus, Web of Science, Google Scholar and ScienceDirect. Studies were selected based on their relevance to the research aims, prioritising peer-reviewed articles and government reports to ensure a robust evidence base.

Key thematic areas included hydrogen combustion emissions and NO_x mitigation, hydrogen leakage risks and atmospheric impacts, amine-based CCS emissions and regulatory concerns and alternative carbon capture solvents with lower environmental trade-offs. Additionally, the review examined air quality impacts and ecological receptor sensitivity in the HyNet region, particularly nitrogen and sulphur deposition at designated sites. These findings informed the broader Phase 4 assessment of air quality in HyNet, highlighting regulatory gaps, technological uncertainties and potential mitigation strategies. The insights gained will support the development of policies and regulatory frameworks for the sustainable deployment of low carbon technology in the HyNet Industrial Cluster.

Image: Protos Energy Recovery Facility with Carbon Capture - latest construction photo provided by Encyclis Limited for use in this Project.

3.3. Stakeholder Engagement

The air quality assessment in HyNet within Phase 4 built upon the stakeholder engagement approach established in earlier phases, focusing on key regulatory agencies, industry representatives and local authorities relevant to air quality considerations. A structured engagement plan was developed to guide interactions, ensuring that the project effectively identified key concerns, knowledge gaps and potential mitigation strategies for air quality impacts associated with low carbon technology in the HyNet industrial cluster.

The engagement aimed to:

- Define the objectives and rationale for stakeholder engagement in the context of industrial decarbonisation.
- Identify key stakeholders, both internal and external, across regulatory bodies, industry and local authorities.
- Apply appropriate engagement techniques tailored to different stakeholder groups.
- Gather insights on current challenges, regulatory gaps and potential mitigation strategies.
- Evaluate stakeholder feedback to inform recommendations and future regulatory considerations.

Two key stakeholder groups were identified: Regulators and Industry. Regulators included the EA, the UK Health Security Agency (UKHSA) and Natural England (NE), with discussions primarily centred on permitting processes, monitoring requirements and cumulative impact assessments. Industry representatives comprised companies involved in hydrogen production and carbon capture, including Viridor, Carlton Power, Tata, Encyclis, Kraft Heinz, ESB Energy, Evero, Progressive Energy and Ineos. These discussions provided first-hand insights into operational constraints, supply chain limitations and the commercial viability of low carbon technology.

Between November 2024 and January 2025, a structured stakeholder engagement process was undertaken to gather insights on air quality impacts, regulatory considerations and industry perspectives within the HyNet industrial cluster. The engagement process included a combination of online and in-person meetings, allowing for broad participation from key stakeholders, including representatives from industry, health and environmental regulators and local authorities.

The engagement activities comprised a series of stakeholder workshops, structured discussions and one-to-one meetings with industry representatives. Workshops provided a platform for information exchange, featuring presentations on regulatory frameworks, emerging research findings and ongoing policy developments relevant to low carbon technology deployment. These sessions encouraged dialogue among participants, fostering collaborative discussions on key challenges and opportunities related to hydrogen production, carbon capture and air quality management.

One-to-one meetings were conducted with industry stakeholders to explore project-specific concerns, technical barriers and sector-specific regulatory challenges. These meetings allowed for in-depth discussions on issues such as permitting complexities, emissions monitoring requirements and the feasibility of implementing enhanced mitigation strategies. Engagement with regulatory bodies also provided valuable insights into policy gaps, enforcement mechanisms and potential improvements to environmental assessment methodologies.

To ensure comprehensive documentation, discussions were transcribed, analysed and thematically categorised. The data collected during these engagements contributed to the evidence base used in this report, providing structured insights into industry needs, regulatory uncertainties and environmental considerations (Environment Agency Phase 4 Annex 2, 2025). The engagement process also served to identify emerging areas of concern, guiding future research priorities and policy recommendations.

4. Stakeholder engagement and review of stakeholder responses

4.1. Evaluation of summaries

Engagement within P4 investigation of air quality in HyNet provided a critical evaluation of air quality impacts, regulatory barriers and infrastructure capacity challenges associated with hydrogen production and CCS in the HyNet industrial cluster. Stakeholder discussions reinforced the importance of improving regulatory clarity, strengthening monitoring frameworks and addressing emerging pollutants such as amines, NO_x and fugitive hydrogen emissions.

Industry representatives, regulators and local authorities provided insight into the evolving environmental and permitting landscape, identifying gaps in air quality assessments, nitrogen deposition mitigation and infrastructure scalability. The engagement process revealed both technical and policy challenges, requiring greater coordination between regulators and industry to enable a structured transition to low carbon industrial development.

Through workshops, structured discussions and targeted one-to-one meetings, stakeholders raised key concerns regarding monitoring limitations, cumulative impact assessment gaps and the need for refined emissions control strategies.

Image: Evero Energy Ince Biomass Energy Recovery Facility.

Key Insights from Stakeholder Engagement

Regulatory and Permitting Challenges:

- Uncertainty surrounding emissions thresholds for novel pollutants remains a major concern. Stakeholders highlighted the lack of standardised EALs for amines and nitrosamines, making compliance assessments difficult.
- Cumulative impact assessments are not sufficiently integrated into permitting processes, particularly for NO_x emissions and nitrogen deposition impacts on designated ecological sites.
- Stakeholders emphasised the complexity of permitting for CCS and hydrogen infrastructure, citing inconsistent regulatory approaches and the absence of sector-wide emissions benchmarks.

Air Quality and Monitoring Gaps:

- Insufficient baseline data on amines, nitrosamines, NH_3 and fugitive hydrogen emissions was a recurring concern.
- The need for a regional monitoring strategy to assess long-term air quality impacts was stressed, ensuring cross-boundary pollution is managed effectively.
- Hydrogen's role as an indirect greenhouse gas was flagged as an area requiring further scrutiny, with stakeholders calling for expanded real-time monitoring networks to assess its impact on methane oxidation and ozone formation.

Ecological and Cumulative Impacts:

- Nitrogen deposition remains a significant issue, with protected sites such as the Mersey Estuary SPA and Manchester Moss SSSI exceeding critical nitrogen thresholds.
- Cumulative impact assessments need further refinement, as existing frameworks do not adequately consider the combined effects of multiple industrial projects. While permitting frameworks such as EPR and HRA do include cumulative emissions considerations, there are gaps in available environmental concentration data for pollutants such as ammonia, hydrogen and nitrosamines. The absence of baseline measurements limits accurate assessments of long-term impacts. Future work should focus on enhancing monitoring networks and improving multi-source dispersion modelling techniques to refine cumulative impact assessments.
- Policy uncertainties regarding emissions offsetting, nutrient pollution and nitrogen mitigation strategies present a major challenge for long-term environmental planning.

Hydrogen Infrastructure and Public Perception:

- The scalability of hydrogen storage, transport and CCS infrastructure remains a challenge, requiring coordinated regulatory and financial support.
- Stakeholders stressed the need for public engagement, particularly in light of recent cancellations of domestic hydrogen trials in Ellesmere Port.
- Misinformation surrounding hydrogen safety and CCS technology was highlighted as a barrier to public acceptance, underscoring the need for transparent risk communication strategies.

Evaluation of Stakeholder Engagement Process

The Phase 4 engagement process successfully gathered industry perspectives, identified regulatory gaps and provided critical input for refining environmental policies.

Strengths of the engagement process:

- One-to-one meetings with industry stakeholders yielded detailed technical insights that would not have emerged from surveys alone.
- Workshops facilitated collaborative dialogue between regulators and industry, helping to align permitting expectations and emissions monitoring approaches.
- The discussions informed key recommendations for strengthening air quality regulations and hydrogen infrastructure planning in the HyNet cluster.

Areas for improvement:

- More structured engagement with local authorities is needed to improve coordination on air quality assessments and industrial planning policies.
- Stakeholder workshops raised complex technical issues, such as the lack of baseline data on amine degradation products, challenges in defining EALs for emerging pollutants and uncertainties in cumulative impact assessments for NO_x emissions from hydrogen combustion. Follow-up sessions with targeted themes, such as regulatory gaps in hydrogen leakage monitoring or the permitting complexities of carbon capture solvents, would enhance clarity and discussion depth.
- Future engagements should focus on dedicated sessions covering cumulative impact assessments, permitting complexities and regulatory uncertainties to address industry concerns more effectively.

The findings from Phase 4 emphasise the urgent need for improved air quality monitoring, enhanced regulatory frameworks and a structured approach to integrating hydrogen and CCS infrastructure. Stakeholder collaboration will remain critical in ensuring that industrial decarbonisation efforts align with environmental objectives and public health safeguards.

5. Evidence Evaluation

5.1 Overview

This section summarises the evidence presented in the technical annexes to assess the environmental capacity of the HyNet industrial cluster to accommodate new low carbon technology while maintaining air quality and protecting sensitive ecological sites. It examines the impacts of hydrogen production and carbon capture on air pollution, particularly NO_2, $PM_{2.5}$, NH_3 and nitrogen deposition, in the context of existing regulatory controls and industrial emissions.

Unlike Teesside, the HyNet region contains multiple Air Quality Management Areas (AQMAs), reflecting persistent exceedances of NO_2 and $PM_{2.5}$ in urban centres such as Liverpool, Manchester, Warrington and Cheshire. The cluster's proximity to sensitive ecological sites, including the Mersey Estuary SPA and Dee Estuary SPA, highlights the importance of emissions control to prevent further nitrogen deposition and acidification impacts.

While national air quality trends show improvements, the introduction of hydrogen combustion and amine-based carbon capture presents new emissions challenges, including increased NO_x emissions, fugitive hydrogen leakage and amine degradation products such as nitrosamines and nitramines. Addressing these issues requires enhanced monitoring, regulatory adaptation and continued research into alternative technologies to mitigate emerging pollutants and their cumulative environmental effects. Further information can be found in Annexes 1-3.

5.2 Current state of the environment

UK air quality continues to improve over time, and air quality data collected in the HyNet industrial cluster follows this trend. However, unlike Teesside, multiple AQMAs have been declared within the HyNet region (Figure 1), particularly in urban centres such as Liverpool, Manchester, Warrington and Cheshire. These declarations reflect exceedances of NO_2 and $PM_{2.5}$ in some areas due to road transport and industrial activities.

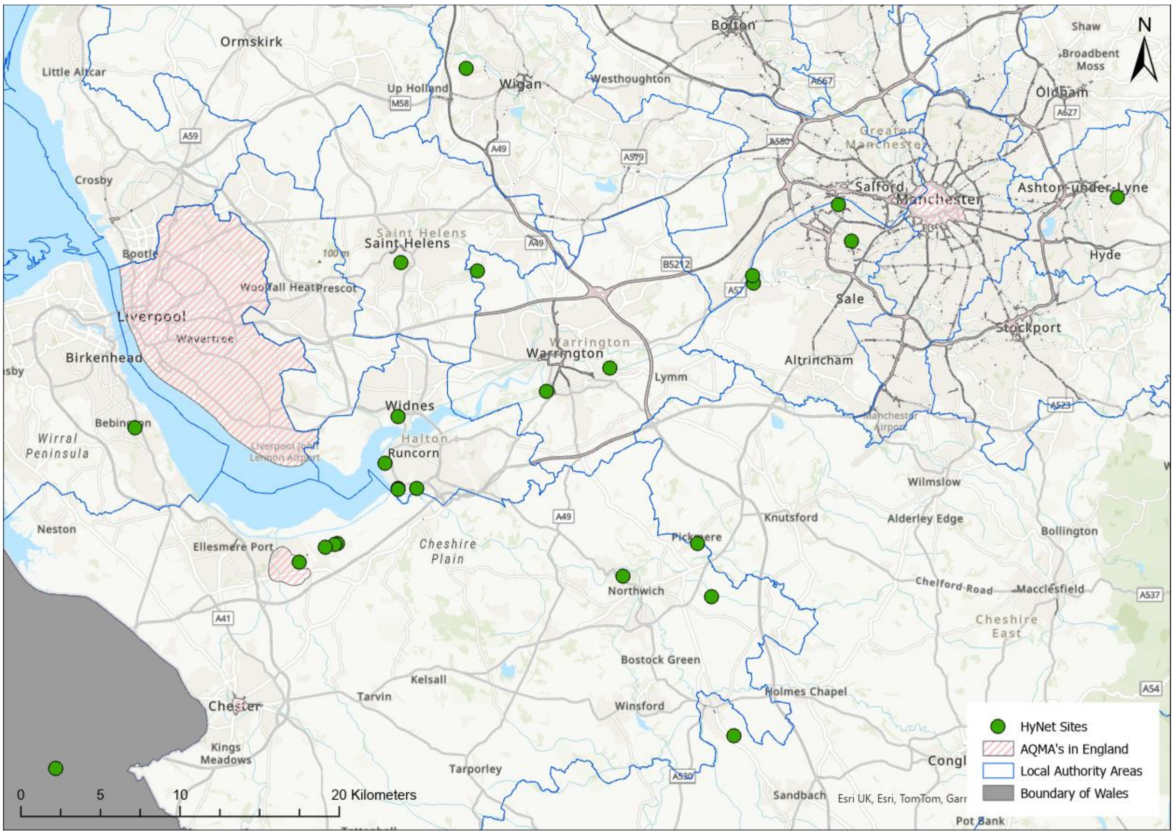

Figure 1: AQMA’s in and around the HyNet Industrial Cluster*

DEFRA, UK Air Information Resource (AIR). Available from: AQMAs interactive map

*This assessment covers air quality within the English portion of the HyNet industrial cluster. Air quality in North Wales is outside the scope of this study, however, the figure includes those HyNet assets which fall within North Wales for illustrative purposes only.

The UK National Atmospheric Emissions Inventory (NAEI) publishes annual estimates of emissions using internationally standardised methods and administrative data from internal and external governmental sources. A summary of UK air pollutant emissions trends has been updated annually since 2012, providing insights into six primary air pollutants: NH_3, NMVOCs, NO_x, PM_{10}, $PM_{2.5}$ and SO_2.

Figure 2, Summary of air pollutants in the UK (NAEI, February 2024), illustrates the long-term trends in UK emissions, showing a clear reduction in atmospheric emissions for all six pollutants since 1970. This decline is primarily driven by tightening industrial and transport regulations and the phase-out of coal use.

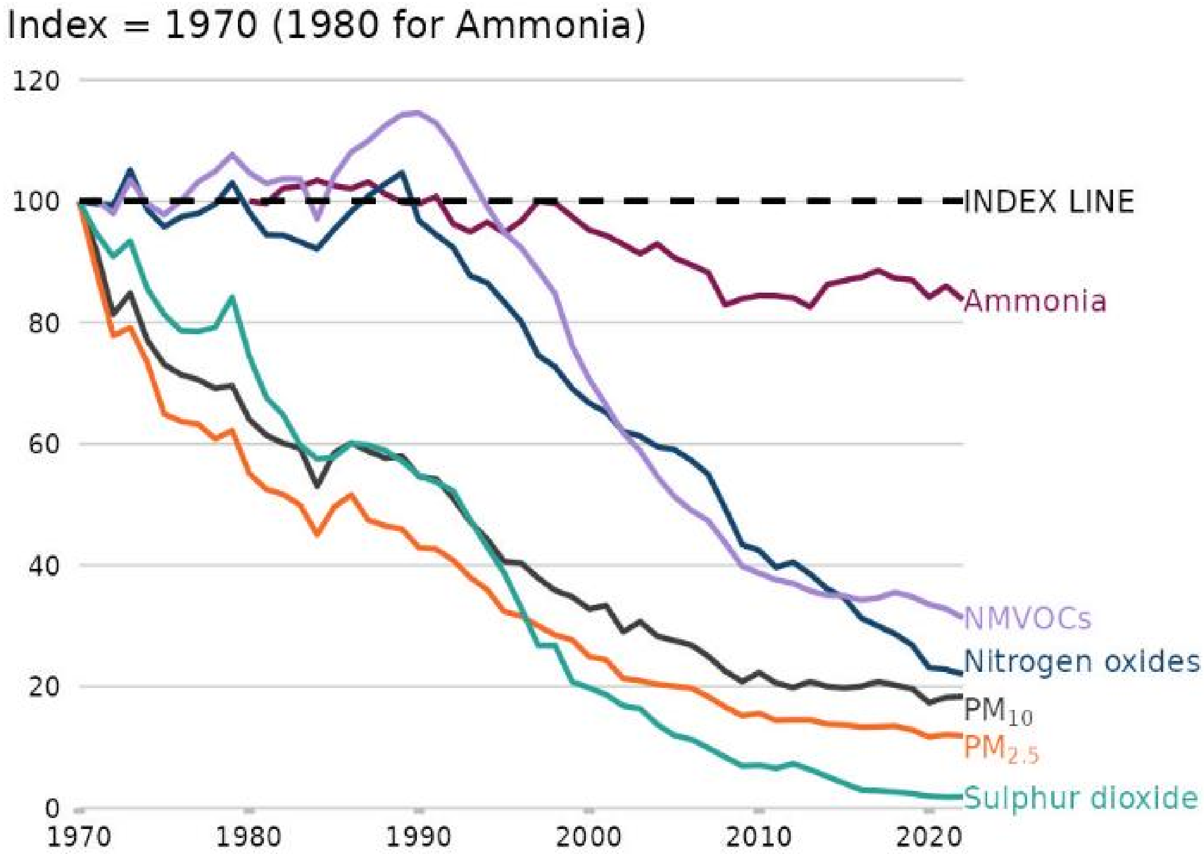

Figure 2: Summary of air pollutants in the UK from the February 2024 NAEI publication illustrates the long-term trends in UK emissions to air.

Within the HyNet industrial cluster, emissions reductions have resulted from shifts in fuel sources, including the transition to hydrogen production. However, NO_2 emissions from hydrogen combustion remain a consideration, particularly for proposed low carbon hydrogen projects in the region. Particulate matter ($PM_{2.5}$) levels also continue to be a concern in industrial zones and urban areas. Despite progress in reducing emissions from traditional sources, nitrogen deposition from agriculture and industrial activities remains a significant environmental challenge, particularly for sensitive ecological sites.

The HyNet region contains both urban centres and designated ecological areas, including the Mersey Estuary Special Protection Area (SPA) and the Dee Estuary SPA. These sites, along with associated SSSIs and Ramsar wetlands, support diverse and fragile habitats that are vulnerable to air pollution impacts. According to the Joint Nature Conservation Committee (JNCC), more than 38% of UK land was sensitive to eutrophication in 2020 and by 2022, a significant portion of sensitive terrestrial habitats still exceeded critical loads for nitrogen and acid deposition (Figure 3). The HyNet region, particularly areas around Cheshire and the Mersey Estuary, includes acid-sensitive and nitrogen-sensitive habitats that face ongoing pressures from atmospheric pollution.

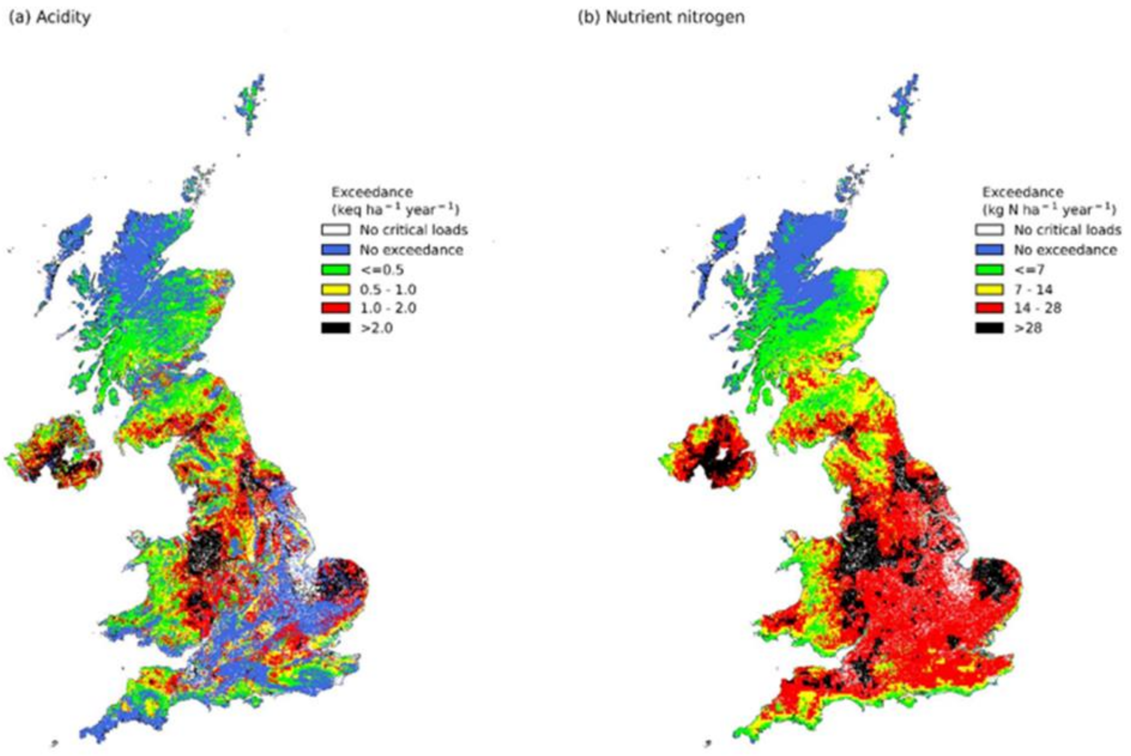

Figure 3: Acidity and Nutrient Nitrogen Critical Load Exceedances in the UK in 2022 (Defra, 2023) with map inserts showing close-up of the Tees industrial cluster area.

NH_3 is both a direct air pollutant and a contributor to nitrogen deposition, particularly affecting sensitive habitats where the critical level for protection is 1 µg/m³. In the HyNet region, ammonia emissions primarily stem from agricultural activities and industrial sources, including amine-based carbon capture, which can lead to solvent degradation into ammonia and other nitrogenous compounds. Some nitrogen-sensitive habitats, such as the Mersey Estuary SPA, may already exceed critical ammonia thresholds. Given recent discussions around ammonia pollution trends, it is essential to continually monitor ammonia levels and assess mitigation measures.

Industrial activities, transport and energy production play a substantial role in shaping air quality in the HyNet cluster. NO_2 and NO_x emissions are concentrated around Stanlow Refinery, with a diffuse pollution zone extending towards Liverpool, Ellesmere Port and Runcorn due to transport emissions. Energy production and transformation processes, including electricity generation at power plants, refining of crude oil and natural gas processing, contribute to nitrogen and sulphur deposition, although their impact is lower than that of transport emissions.

Image: Stanlow Refinery in Ellesmere Port. Image supplied by Essar Energy for use in this Project. Image is of Stanlow refinery with the Catalytic Cracker in the background.

While coal combustion has declined, leading to a reduction in NO_x and SO_x emissions, new industrial processes, including hydrogen production and carbon capture, introduce specific challenges. Hydrogen combustion can increase NO_x emissions due to high flame temperatures, while solvent-based carbon capture systems may lead to secondary emissions, such as NH_3 and degradation products, which require careful monitoring.

The Mersey Estuary SPA and SSSI encompass extensive intertidal mudflats, saltmarsh and freshwater habitats, shaped over time by industrial activity and natural estuarine processes. These areas are particularly sensitive to nitrogen enrichment and acid deposition, which can alter plant community composition, reduce biodiversity and impact water quality. Critical loads within these sites are habitat and feature-specific, reflecting the varying sensitivity of ecosystems to airborne pollutants. The lowest applicable critical load class within the Mersey Estuary SPA is saltmarsh habitat, which is found downwind of the HyNet industrial cluster and adjacent to major industrial areas such as Stanlow Refinery and Runcorn industrial complex.

Figures provided in Annex 3 (Environment Agency Phase 4 Annex 3, 2025) illustrate the estimated background concentrations of key pollutants, such as NO_x, NO_2, PM_{10}, $PM_{2.5}$, SO_2 and NH_3, associated with industrial activities in the HyNet area, with projections for 2024 based on a 2021 baseline. These maps highlight emission hotspots and background pollution levels near key industrial assets, showing that nitrogen deposition levels in several locations exceed critical thresholds. The distribution of PM_{10} and $PM_{2.5}$ is relatively uniform across the region, with slightly elevated levels along major transport routes, including the M56 and M62 corridors, where road vehicle emissions remain a primary contributor. Shipping emissions also play a role in local air quality, particularly in areas surrounding Liverpool's port operations.

Most NH_3 pollution in the HyNet region originates from agricultural practices, but industrial emissions must be carefully managed to prevent additional deterioration of protected habitats. As hydrogen-fuelled and electric vehicles (EVs) replace conventional diesel and petrol vehicles, NO_x and PM emissions from transport are expected to decline. However, the introduction of new industrial projects, including large-scale hydrogen production and carbon capture, may alter the emissions profile of the region. A review of the current air quality monitoring network is recommended to ensure that changes in pollution levels and their ecological impacts are adequately captured. Some pollutants, particularly nitrogen compounds and fine particulate matter, can be transported over long distances, potentially influencing air quality in adjacent regions and beyond.

While the shift towards hydrogen and carbon capture technologies presents opportunities for industrial decarbonisation, their associated air quality impacts require ongoing assessment and management. Ensuring that these processes do not contribute to increased nitrogen deposition, acidification, or particulate pollution is essential for balancing industrial development with the long-term protection of the region's sensitive ecological sites. Continued collaboration between industry and regulators will be critical in maintaining air quality improvements while supporting the transition to a low carbon energy system.

5.3 Review of proposed low carbon technologies

Low carbon technologies in HyNet

The HyNet Industrial Cluster is a key part of the UK's decarbonisation strategy, integrating hydrogen production, carbon capture and storage technologies to support industrial emissions reduction while ensuring energy security. HyNet is positioned as a pioneer for large-scale hydrogen adoption and industrial decarbonisation, leveraging existing infrastructure, underground gas storage and carbon sequestration sites. However, while these technologies offer significant opportunities for carbon emissions reduction, they also present challenges related to nitrogen deposition, air quality, water resources and regulatory adaptation.

The HyNet industrial cluster is a key hub for energy production, industrial manufacturing and emerging low carbon technology. With a strong industrial base spanning petrochemical processing, hydrogen production and carbon capture initiatives, the cluster is positioned as a leading centre for decarbonisation efforts in the UK. Government policies, investments and subsidies have accelerated the transition towards low carbon energy, with an increasing number of projects focused on carbon capture, hydrogen production and hydrogen utilisation. This shift is driven by national net-zero commitments and the strategic advantages offered by the region's existing industrial infrastructure.

Unlike other industrial clusters, HyNet benefits from its proximity to extensive pipeline networks, underground storage facilities and existing refining and chemical processing infrastructure. This integrated network allows for the efficient transportation and storage of captured carbon dioxide, as well as the distribution of low carbon hydrogen to key industrial and commercial users. Additionally, the availability of water resources for industrial processes, particularly in Cheshire and the Mersey Estuary, supports large-scale hydrogen production and carbon capture operations without the same constraints faced by other clusters with more limited water supply.

The geographical positioning of the HyNet cluster offers further strategic advantages. Its location within the North West of England and North Wales provides access to both domestic and international markets, while its connection to offshore carbon storage sites via pipeline infrastructure enhances its long-term viability for carbon sequestration. This geographic compactness facilitates the clustering of industries, allowing for greater integration and optimisation of low carbon technology (Figure 4). Over 50 projects have announced plans to decarbonise within the HyNet cluster, with more than 30 focused on carbon capture, hydrogen production, or hydrogen utilisation. These projects span a range of sectors, including refining, chemical manufacturing and energy generation.

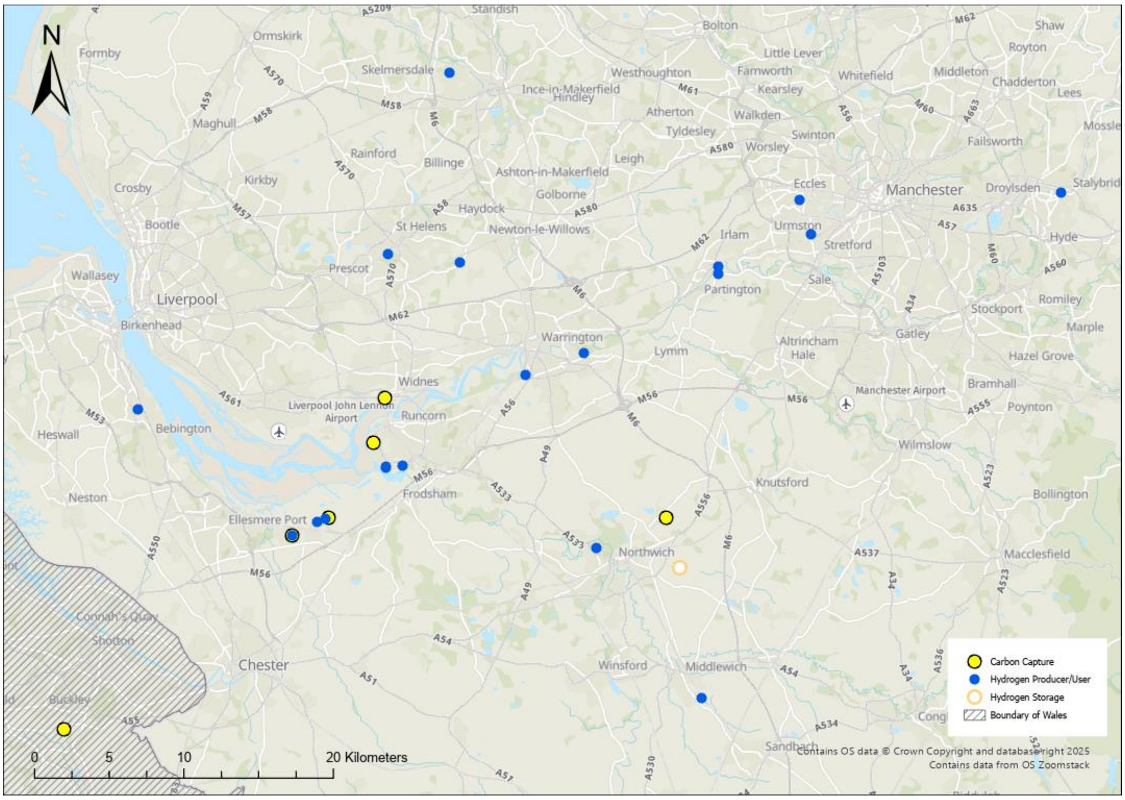

Figure 4: Projects within the HyNet industrial cluster*

*This assessment covers air quality within the English portion of the HyNet industrial cluster. Air quality in North Wales is outside the scope of this study, however, the figure includes those HyNet assets which fall within North Wales for illustrative purposes only.

Many of these projects are concentrated within industrial zones such as Stanlow Refinery, Runcorn industrial complex and Ellesmere Port, benefiting from existing infrastructure, regulatory incentives and proximity to key distribution networks (Figure 5). Within these industrial areas, significant new investments are being made to support hydrogen production and carbon capture initiatives, with new sites requiring environmental permits to operate. Existing facilities retrofitting carbon capture technology or transitioning to hydrogen as a fuel source will require modifications to their permits to reflect changes in emissions profiles and operational processes.

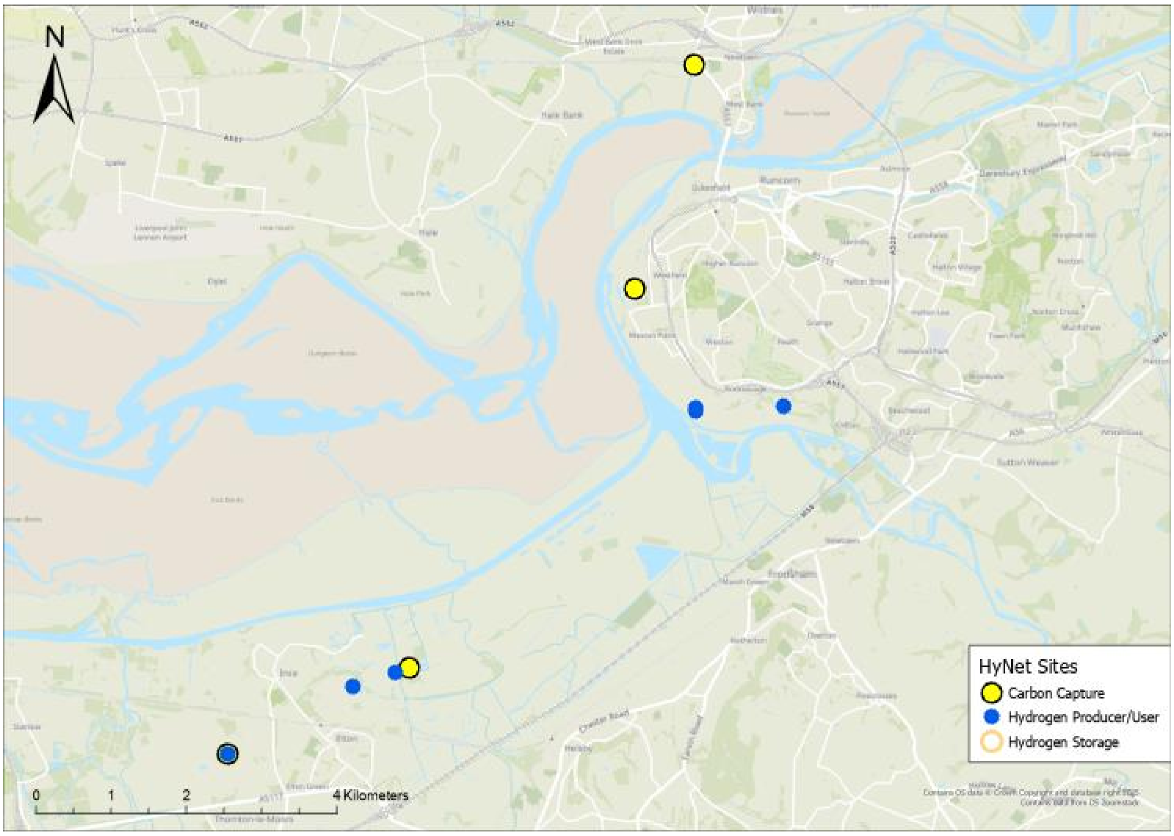

Figure 5: Projects within the Ellesmere Port Area

This section summarises the status of proposed hydrogen and Carbon Capture, Utilisation and Storage (CCUS) projects within the HyNet Industrial Cluster, focusing on current deployment, environmental impacts and air quality considerations, as outlined in Annex 3 of Phase 4 air quality in HyNet (Environment Agency Phase 4 Annex 3, 2025) and the Phase 3 Report (Environment Agency Phase 3 Report, 2024).

Hydrogen Production, Storage and Use in HyNet

Hydrogen is a central pillar of HyNet's low carbon transition, with multiple projects at different stages of development. The production and use of hydrogen within the cluster is expected to significantly contribute to net-zero targets, with both blue and green hydrogen projects in operation or planned.

Blue hydrogen production, which combines steam methane reforming (SMR) with carbon capture, is a core part of HyNet's near-term industrial decarbonisation efforts. The Essar/Vertex Hydrogen (Phase 1) project is a major blue hydrogen production site, designed to produce compressed hydrogen at 99.9% purity from natural gas and refinery off-gas, while capturing CO_2 directly from the syngas process stream rather than post-combustion (Environment Agency Phase 4 Annex 3, 2025). The project is integrated into HyNet's CO_2 transportation and storage network, enabling long-term sequestration in depleted gas fields in Liverpool Bay.

In addition to blue hydrogen, green hydrogen production is expanding across HyNet, relying on electrolysis powered by renewable electricity. The Cheshire Green Hydrogen project at Protos (Ince) and Carlton Power's Trafford Green Hydrogen Plant will supply low carbon hydrogen for industrial users, reducing reliance on fossil fuels. Electrolysers in these facilities are designed to operate at up to 30MW capacity, with a daily production rate of nearly 13,000 kg of hydrogen (Environment Agency, 2025). Green hydrogen production is widely considered to be the most sustainable long-term alternative, yet with a high electricity demand, efficiency constraints and cost remain barriers to large-scale deployment (Environment Agency Phase 3 Report, 2024).

Beyond production, hydrogen storage and distribution infrastructure are also a key feature of HyNet's development. The Keuper Gas Storage Project, previously used for natural gas, is being converted to store up to 1,300 GWh of hydrogen in underground salt caverns in Cheshire, with plans for the creation of additional salt caverns to expand storage capacity (Environment Agency Phase 4 Annex 2, 2025). Large-scale hydrogen storage is critical for balancing supply and demand, particularly in energy-intensive industries where continuous hydrogen availability is required. However, hydrogen leakage presents environmental and climate challenges, as hydrogen is a potent indirect greenhouse gas that influences methane and ozone formation (Ocko & Hamburg, 2022). Ensuring proper containment, material compatibility, and real-time leak detection remains a regulatory priority.

Hydrogen storage is a critical component of the HyNet network, ensuring reliable supply for industrial users and mitigating renewable energy intermittency. While UHS in salt caverns presents a scalable solution, it is not without challenges. Hydrogen's small molecular size makes it susceptible to leakage in porous formations such as aquifers, necessitating advanced material coatings and containment strategies (Zivar et al., 2020). Microbial activity in geological formations can also lead to hydrogen losses through methanation and sulphate reduction, further complicating long-term storage reliability (Pan et al., 2021).

Leakage from UHS follows a source-pathway-receptor mechanism: hydrogen escaping from storage (source) can migrate through subsurface formations (pathway) and be released into the atmosphere via diffusion through caprock, migration along well casings, or venting from the facility. Methanation underground may further increase emissions of methane (CH_4), a potent greenhouse gas, while sulphate reduction can lead to hydrogen sulphide (H_2S) emissions, affecting air quality and human health (Zivar et al., 2020). Once in the atmosphere, hydrogen leakage can prolong the lifetime of methane, alter tropospheric ozone chemistry and indirectly contribute to climate forcing. Additionally, interactions with NO_x and VOCs may influence urban and industrial air pollution patterns. Addressing these challenges requires ongoing research into material sciences, geological assessments and advanced monitoring technologies.

Hydrogen is also being trialled for industrial fuel switching, with multiple projects exploring gradual adoption of hydrogen as a replacement for natural gas. Several industrial users, including Pilkington Glass (St Helens), Encirc Glass (Elton), Novelis (Warrington), Unilever (Wirral) and Kellogg's (Manchester), are in different stages of testing hydrogen combustion in manufacturing processes (Environment Agency Phase 4 Annex 3, 2025). Some large-scale energy facilities, such as Carrington Power Station and Rocksavage Power Station, are planning to blend hydrogen with natural gas, with long-term goals of 100% hydrogen conversion.

While hydrogen combustion eliminates CO_2 emissions, it has the potential to increase NO_x emissions by up to 40% compared to methane combustion, particularly if high-temperature hydrogen flames are not mitigated through low-NO_x burners or SCR technologies (Boningari & Smirniotis, 2016). The Phase 3 Report highlighted that NO_x formation from hydrogen combustion requires comprehensive air quality monitoring and emissions control to ensure compliance with local air quality standards (Environment Agency Phase 3 Report, 2024).

Carbon Capture, Utilisation and Storage in HyNet

CCUS is a critical component of HyNet's emissions reduction strategy, enabling the capture of CO_2 from industrial processes within the cluster. HyNet's CCUS infrastructure is designed to transport captured CO_2 via pipeline to offshore storage sites, reducing atmospheric CO_2 emissions from industrial operations.

Several projects within the cluster have committed to large-scale CCUS deployment. The Protos Encyclis Energy Recovery Facility (ERF) and Runcorn Viridor ERF projects plan to capture over 1.2 million tonnes of CO_2 per year, utilising amine-based solvents to separate CO_2 from flue gases before transport to HyNet's CO_2 storage network (Environment Agency Phase 4 Annex 2, 2025). The Padeswood Cement Works is located within the wider HyNet region but falls outside the scope of this report as it is situated within North Wales and regulated by Natural Resources Wales (NRW).

Image: Protos Energy Recovery Facility with Carbon Capture – image shows the Encyclis ERF under construction (left of picture) which was recently permitted for CCS and the operational Evero Energy biomass ERF (right of picture) with proposed CCS plant in foreground.

While amine-based carbon capture remains the most widely deployed technology, it presents environmental concerns related to solvent degradation, emissions of nitrosamines and nitramines and potential atmospheric deposition of NH_3 (Gjernes et al., 2013). These compounds, known for their carcinogenic and toxic properties, require robust emissions monitoring and regulatory controls (Environment Agency Phase 3 Annex 1, 2024). Some operators within HyNet, including Evero and Viridor, have structured permit applications around MEA-based solvent capture while considering transitions to proprietary, lower-impact solvents in the future (Environment Agency Phase 4 Annex 2, 2025).

The Department for Department for Business, Energy and Industrial Strategy (BEIS) sponsored study into next generation carbon capture technology (Department for Business, Energy and Industrial Strategy, 2022) presents a review and technoeconomic analysis of next generation carbon capture technologies. The study presents the potential application of carbon capture technology to different industrial, waste and power sites focused on technologies with the potential to be deployed at a scale of the order of 1,000 ton per day of CO_2 capture by 2030. Less well-developed technologies that are more likely to be deployed at scale by 2035, or later, are also presented in the report but with a lower level of detail.

Alternative CO_2 capture methods being explored include Ionic liquids, MOFs and enzyme-based capture systems offer potential reductions in energy consumption while minimising secondary emissions (Ab Rahim et al., 2023). These emerging technologies demonstrate promising efficiency gains, with some ionic liquid formulations achieving 20-40% energy savings compared to traditional solvents. However, further pilot studies and regulatory adaptation are required before large-scale deployment within HyNet's industrial sites (Environment Agency Phase 4 Annex 1, 2025).

Air Quality and Environmental Considerations

The expansion of hydrogen and CCUS technologies in HyNet introduces new air quality considerations, particularly in areas with existing AQMAs such as Liverpool, Manchester and Warrington (Environment Agency Phase 4 Annex 3, 2025).

- Hydrogen combustion and NO_x emissions: Without proper emission control, the transition to hydrogen-fuelled combustion could lead to elevated NO_x levels, affecting compliance with air quality standards (Environment Agency Phase 3 Report, 2024).
- NH_3 emissions from CCUS: Amines used in carbon capture degrade into NH_3 and nitrogenous compounds, contributing to nitrogen deposition in ecologically sensitive areas such as the Mersey Estuary SPA and Dee Estuary SPA (Environment Agency Phase 4 Annex 3, 2025).
- Cumulative impact assessments: Current air quality monitoring networks do not fully account for hydrogen-related emissions, amine degradation byproducts, or long-range nitrogen transport, requiring strategic monitoring expansions (Environment Agency Phase 4 Annex 1, 2025; Environment Agency Phase 3 Annex 1, 2024).

Future Considerations

While HyNet's deployment of low carbon technologies is a key step towards net zero, future efforts should focus on NO_x mitigation, hydrogen leakage monitoring and alternative CCUS solvents to ensure long-term sustainability. Expanding environmental monitoring frameworks and cumulative impact assessments will be crucial in balancing industrial growth with air quality and ecological protection.

Further research is required to address knowledge gaps in hydrogen production, combustion emissions and carbon capture technology performance. Key priorities include conducting lifecycle assessments of hydrogen production and combustion, particularly regarding NO_x formation and leakage risks and evaluating alternative non-amine solvents and advanced CO_2 capture materials to mitigate environmental and health risks (Environment Agency Phase 4 Annex 1, 2025; Environment Agency Phase 4 Annex 3, 2025). Additionally, continuous monitoring of atmospheric nitrogen deposition is necessary to assess its potential impacts on sensitive ecological sites within the HyNet region. Regulatory development is also crucial to enhance permitting processes for hydrogen and CCUS projects, ensuring that emerging technologies align with evolving emissions standards (Environment Agency Phase 3 Report, 2024).

Health and Environmental Impacts

The health and environmental impacts of carbon capture and hydrogen technologies have been widely studied, particularly regarding emissions, air quality effects and potential risks to human health and ecosystems. Amine-based carbon capture systems have drawn attention due to the formation of nitrosamines and nitramines, which are known for their carcinogenic and toxic properties. These compounds, formed during solvent degradation, have varying persistence in the environment, with nitramines exhibiting greater stability and potential for long-term accumulation (Gjernes et al., 2013).

Regulatory thresholds have been set in some jurisdictions, such as Norway's temporary exposure limits of 0.3 ng/m^3 for air and 4 ng/L for drinking water (de Koeijer et al., 2013), showing the need for robust emission monitoring and mitigation measures. Studies have also highlighted the influence of meteorological conditions on the dispersion and deposition of these compounds, with colder, stable atmospheric conditions leading to increased ground-level concentrations (Wu and Nelson, 2014). However, recent mitigation strategies, such as ultraviolet (UV) treatment and advanced scrubbing systems, have demonstrated effectiveness in significantly reducing these emissions (de Koeijer et al., 2013).

Hydrogen production and use present distinct environmental challenges. While green hydrogen offers a zero-carbon fuel alternative, its combustion can increase NO_x emissions due to higher flame temperatures. Without proper emission control technologies, such as SCR or advanced burner designs, hydrogen use in industry and transport could lead to elevated NO_x levels, affecting local air quality (Gür, 2022). Additionally, hydrogen's small molecular size increases the risk of leakage throughout its supply chain. Studies suggest that global leakage rates of 1–10% could prolong the atmospheric lifetime of methane and increase tropospheric ozone, counteracting some climate benefits of hydrogen adoption (Ocko and Hamburg, 2022). Within the HyNet industrial cluster, efforts are being made to minimise these risks through improved pipeline materials, advanced sealing technologies and real-time leak detection systems.

Occupational health risks are also a consideration for both hydrogen and carbon capture technologies. Exposure to MEA vapours used in carbon capture has been linked to neurological effects, while hydrogen leakage poses flammability and asphyxiation risks in confined spaces (Reuters Events, 2023). Mitigating these hazards requires stringent workplace safety protocols and continuous monitoring of industrial processes.

Image: Stanlow Refinery in Ellesmere Port. Image supplied for use by Essar Energy. – Image is of the new furnace, which is the first of its kind in the UK, capable of running on a 100% hydrogen source and will replace three existing furnaces at Stanlow. It is helping to reduce CO_2 emissions by more than 240,000 tonnes each year from 2027.

Climate change projections introduce further challenges for carbon capture efficiency. Rising temperatures and seasonal variability can influence solvent performance, with studies indicating that capture efficiency declines significantly in colder, drier conditions (An et al., 2022). Similarly, water demand for solvent regeneration may become a limiting factor in regions with drier summers, necessitating improved water recycling and management strategies (Peppas et al., 2023).

A comprehensive environmental monitoring framework is required to assess the long-term impacts of these technologies on air quality, water resources and ecosystems. This should include:

- Lifecycle assessments of hydrogen production and combustion, particularly regarding NO_x emissions and leakage risks.
- Long-term studies on the effectiveness and environmental risks of amine-based carbon capture, including emissions of nitrosamines and nitramines.
- Continuous monitoring and modelling to refine projections of air quality within the HyNet cluster.
- Research into alternative non-amine solvents and advanced carbon capture materials to reduce environmental and health risks.

Addressing these challenges through sustained monitoring, improved regulatory standards and technological innovation will be essential to ensuring the successful deployment of low carbon technologies while safeguarding human health and environmental integrity.

5.4 Climate impact changes to the baseline

Climate change is expected to influence the environmental conditions within the HyNet cluster, particularly through rising temperatures, altered precipitation patterns and changes in air and water quality. Projections indicate that by 2040-2059, annual maximum daily temperatures could increase by up to 2.66°C under high emissions scenarios (RCP5-8.5), with potential impacts on industrial cooling systems, emissions control and operational efficiency (Figure 6) (Environment Agency Phase 4 Annex 3, 2025). Annual precipitation is expected to remain relatively stable but could experience seasonal variations, with wetter autumns and drier summers increasing pressure on water availability for industrial processes (Figure 7) (Environment Agency Phase 4 Annex 3, 2025).

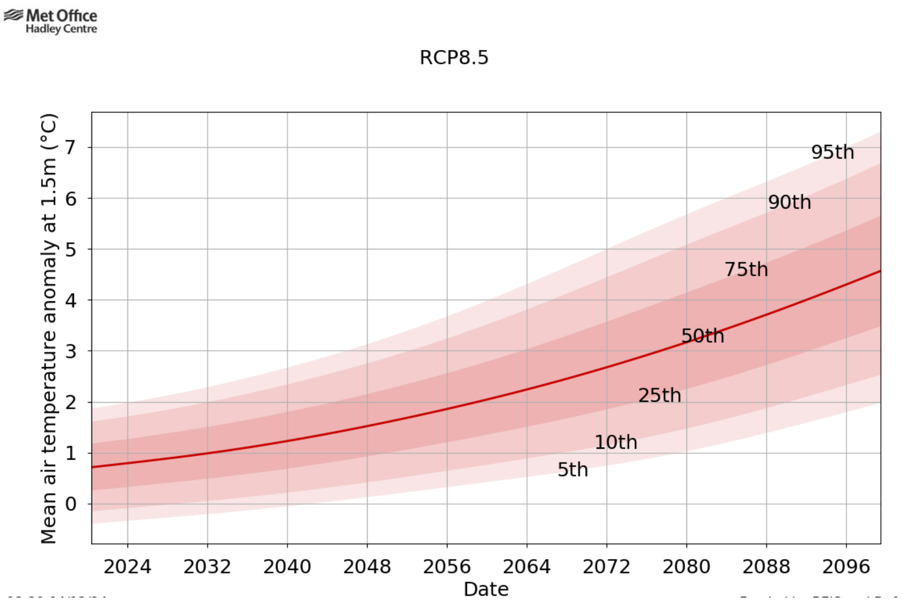

Figure 6: Temperature Projections within the HyNet Cluster – High Emission Scenario

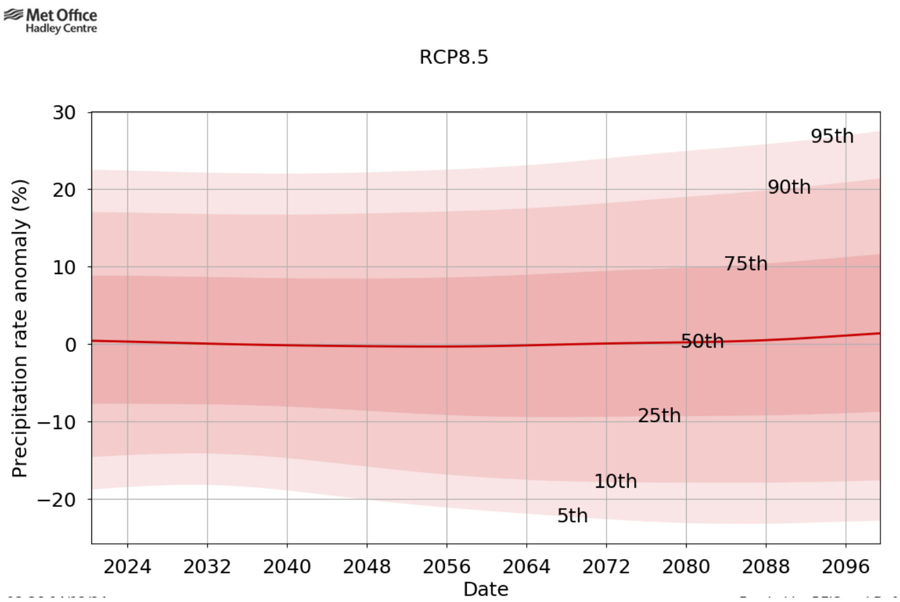

Figure 7: Precipitation Projections of Air Pollutants in the UK – High Emission Scenario

These climatic changes may exacerbate air quality issues within the cluster. Rising temperatures can accelerate the formation of ground-level ozone and increase nitrogen deposition, further impacting local ecological receptors. While NO_2 concentrations in the region have shown a downward trend, ongoing industrial expansion and higher ambient temperatures could slow progress in improving air quality (Environment Agency Phase 4 Annex 3, 2025). Additionally, climate variability may influence the efficiency of carbon capture and hydrogen technologies, requiring adaptive regulatory and technological measures to mitigate unintended environmental consequences.

6. Conclusions and Recommendations

This air quality review of the HyNet industrial cluster has assessed the environmental and regulatory capacity for deploying carbon capture and hydrogen production technologies. While these low carbon solutions are fundamental to industrial decarbonisation, they introduce new challenges that must be addressed to ensure environmental protection and regulatory compliance.

Hydrogen combustion presents a significant air quality concern as it generates NO_x emissions. While the EA has established EALs for NO_x, regulatory challenges remain regarding the application of emissions control technologies, particularly for smaller MCPD units and hydrogen blends in natural gas pipelines. Without stricter emissions controls and clearer regulatory frameworks, these pollutants could offset anticipated air quality improvements. Additionally, fugitive hydrogen leakage, although not directly harmful, poses climate implications due to its ability to prolong methane's atmospheric lifetime, highlighting the need for enhanced detection and monitoring systems.

Amine-based carbon capture technologies continue to dominate the sector, yet concerns remain over nitrosamine and nitramine formation, which require improved regulatory oversight. While research into alternative non-amine solvents, such as ionic liquids and MOFs, has shown promise, further development is needed to reduce secondary emissions and improve capture efficiency.

The cumulative environmental impacts of industrial expansion in HyNet, particularly nitrogen and sulphur deposition, present additional challenges. Sensitive ecological receptors, such as Holcroft Moss and the Mersey Estuary, are already experiencing nitrogen levels that exceed critical thresholds, necessitating mitigation strategies to prevent further degradation. Strengthening regional air quality monitoring networks and incorporating cumulative impact assessments into permitting processes will be essential for managing these risks.

The regulatory landscape for hydrogen production, CCS and associated infrastructure remains fragmented, creating uncertainty for project developers. Clearer permitting pathways are needed to support the expansion of hydrogen storage, CO_2 transport and industrial retrofits, while ensuring that emerging pollutants do not compromise air quality or ecological health.

This assessment focuses solely on the regulatory and environmental considerations within England. Environmental matters in Wales, including permitting frameworks and site-specific air quality impacts, are devolved to Welsh Ministers and fall outside the scope of this report. Further research would be required to evaluate similar considerations in the Welsh portion of the HyNet region.

Air quality review in HyNet in this report builds on previous project phases by identifying air quality risks, regulatory gaps and infrastructure challenges associated with deploying low carbon technologies. While the UK has made progress in reducing NO_2 concentrations, background nitrogen deposition remains above ecological thresholds, particularly in sensitive habitats. This creates regulatory and permitting hurdles that must be addressed to ensure that industrial expansion does not further degrade ecological receptors.

Regulatory oversight for amine-based carbon capture solvents and hydrogen storage infrastructure remains inconsistent, leading to uncertainty for project developers. Additionally, fugitive hydrogen leakage and NO_x emissions from combustion present new air quality risks that require enhanced monitoring and mitigation strategies.

A strategic, whole-system approach is needed to ensure that hydrogen and CCS deployment aligns with environmental protection goals. Future efforts should focus on integrating air quality impacts, water resource constraints and hydrogen leakage risks into permitting processes, while fostering industry collaboration to address cumulative emissions impacts.

It is also critical that hydrogen and CCS projects do not introduce new, long-lived greenhouse gas emissions or secondary pollutants through transport and storage which could compromise air quality and environmental integrity.

Recommendations for Air Quality in HyNet

Some recommendations from Phase 3 remain highly relevant to HyNet due to similar air quality, permitting and emissions control challenges. These include:

1. Strengthen Air Quality Monitoring and Emissions Control

   Expanding baseline air quality monitoring for amines, nitrosamines, NH_3 and fugitive hydrogen will be crucial. The development of EALs and emissions control limits for novel pollutants should be prioritised alongside improved cumulative impact assessments for NO_x emissions from hydrogen combustion and nitrogen deposition risks. Establishing a UK-based laboratory capability for accredited nitrosamine and nitramine testing will also ensure that regulatory requirements are met in process permits.

2. Address Regulatory Gaps in Carbon Capture and Hydrogen Infrastructure

   Standardising permitting processes for CCUS and hydrogen projects will provide greater clarity for industry. While EALs for NO_x from hydrogen combustion have been established, further regulatory clarity on appropriate emissions control techniques, such as water injection, low-NO_x burners and alternative abatement strategies for smaller-scale combustion units, would help industry align with air quality objectives.

3. Enhance Infrastructure Resilience and Climate Adaptation

   Flood resilience should be integrated into site selection for hydrogen and CO_2 transport infrastructure. Additionally, establishing emergency response protocols for hydrogen venting and CO_2 leakage risks will be key to ensuring safe operations.

4. Encourage Research into Non-Amine-Based CCS Solvents

   Investigating the potential for alternative solvents, such as ionic liquids, deep eutectic solvents and MOFs, could offer lower-emission alternatives to amine-based capture systems. Research into retrofitting alternative solvents to existing CCS infrastructure should also be explored.

5. Strategic Industrial Growth Planning and Site Selection

   Given nitrogen deposition constraints, growth at existing sites may be limited, encouraging industries to relocate to areas with better access to nitrogen offsetting or CCS pipelines. Spatial planning frameworks should be developed to consider nitrogen deposition impacts and air quality capacity when siting new hydrogen production and CCS facilities.

6. Improve Stakeholder Coordination on Hydrogen Infrastructure Expansion

   Clearer regulatory approval pathways are needed for hydrogen pipelines and storage facilities, alongside stronger cross-industry collaboration to optimise distribution networks and integrate hydrogen into regional decarbonisation strategies.

Evidence Gaps and Areas for Research

To ensure the sustainability of industrial cluster development and the contribution towards decarbonisation, further research is required in the following areas:

1. Developing predictive models for nitrogen deposition and cumulative air quality impacts to ensure regulatory thresholds remain protective of sensitive ecosystems.
2. Investigating fugitive hydrogen emissions and their role in atmospheric chemistry, particularly their indirect effects on methane and ozone concentrations.
3. Advancing alternative CCUS technologies and low-NO_x hydrogen combustion strategies. Improving the efficiency and environmental performance of these processes.
4. Exploring potential synergies between hydrogen production, carbon capture and bioenergy, optimising industrial decarbonisation strategies.
5. Developing area-wide digital modelling and air quality monitoring networks to improve the understanding of cumulative industrial emissions.

The HyNet Industrial Cluster represents a critical test case for deploying hydrogen and CCS technologies in the UK. However, air quality concerns, permitting uncertainties and infrastructure challenges must be addressed to ensure sustainable industrial development.

The findings from the review of air quality in HyNet reinforce the need for an integrated regulatory approach, enhanced air quality monitoring and targeted research investments to manage environmental risks effectively. Moving forward, continued collaboration among regulators, industry leaders and policymakers will be essential to ensure that low carbon technologies support the UK's decarbonisation goals while safeguarding environmental and public health protection.

Image: Part of the Runcorn Chemical Complex as seen from the Manchester Ship Canal. Image captured by the EA.

7. Acronyms

AQMAs	Air Quality Management Areas
AQS	Air Quality Standards
BECCS	Bioenergy Carbon Capture and Storage
BEIS	Department for Business, Energy and Industrial Strategy
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Storage
CHP	Combined Heat and Power
COMAH	Control of Major Accidents and Hazards Regulations
DAC	Direct Air Capture
DEA	Diethanolamine
DESNZ	Department for Energy Security and Net Zero
EA	Environment Agency
EALs	Environmental Assessment Levels
EFW	Energy from Waste
EPR	Environmental Permitting Regulations (England and Wales) 2016
ERF	Energy Recovery Facility
EV	Electric Vehicle
HECC	Health and Environmental Impacts of Carbon Capture
HRA	Habitat Regulations Assessment
JNCC	Joint Nature Conservation Committee
MDEA	Methyldiethanolamine
MEA	Monoethanolamine
N	Nutrient

Na	Sodium
NAEI	National Atmospheric Emissions Inventory
N-amines	A Broad Category of Nitrogen-Containing Amines, Including Nitrosamines and Nitramines
NaOH	Sodium Hydroxide
NDEA	N-Nitrosodiethylamine
NDMA	N-Nitrosodimethylamine
NE	Natural England
NH_3	Ammonia
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxide
NPIP	N-Nitrosopiperidine
NZT	Net Zero Teesside
NZT	Net Zero Teesside
OEMs	Original Equipment Manufacturers
PBDE	Polybrominated Diphenyl Ethers
PCBs	Polychlorinated Biphenyls
PCC	Post-combustion Carbon Capture
PM_{10}	Particulate Matter with an aerodynamic diameter of less than 10 micrometres (µm)
$PM_{2.5}$	Particulate Matter with an aerodynamic diameter of less than 2.5 micrometres (µm)
SACs	Special Areas of Conservation
SMR	Steam-methane Reforming
SO_2	Sulphur Dioxide
SPA	Special Protected Area
SSP	Strategic Spatial Planning

SSSI	Site of Special Scientific Interest
UKHSA	UK Health Security Agency
VOC’s	Volatile Organic Compounds

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