Environmental Capacity in Industrial Clusters

Phase 3

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Contents

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. This work aims to support UK Government's Net Zero Strategy and enable successful sustainable development of low carbon industrial clusters. As the environmental regulator in England, the EA plays an important role in enabling the development of industrial clusters to meet emissions targets and safeguard the environment, through our regulation and advice in leading sectors.

This third phase of work reviews environmental capacity challenges in the Teesside and HyNet industrial clusters, to understand cumulative industry plans at the industrial cluster scale alongside a review of the impacts that deployments may have on the environment. This includes considering water availability and water quality in the HyNet industrial cluster, air quality and unintended consequences on ecological receptors in the Teesside industrial cluster. It also considers how these factors will be influenced by a changing climate.

In previous years Phase 1 (2021-2022) considered water availability and water quality in the Humber industrial cluster. Phase 2 (2022-2023) took a deeper look at environmental capacity in the Humber including, air quality and flood risk. Phase 2 also expanded a review of the environmental challenges for the East Coast cluster by considering water availability and water quality in the Teesside industrial cluster. Phase 3 (2023-2024) expands the environmental challenges considered in Teesside with a look at air quality impacts, and a review of water availability and water quality in the HyNet industrial cluster.

This phase extends the approach taken in previous studies. to explore the state of the environment, industry plans and the capacity of the environment to enable carbon capture and hydrogen production in the Teesside and HyNet industrial clusters. Stakeholder engagement has developed from lessons learnt from Phases 1 and 2 by expanding our engagement with industry, in particular representatives from the carbon capture and hydrogen trade associations, engaging through workshops and individual discussions.

Understanding the potential for air quality impacts plays a critically important role in the sustainable delivery of a net zero future. Air quality must continue to improve and not be substituted by other potentially harmful substances while driving down carbon dioxide (CO_2) emissions. Teesside is experiencing improvement in air quality, where the annual average nitrogen dioxide (NO_2) concentration in Redcar and Cleveland has decreased from 24μg/m³ in 2018 to 13.9μg/m³ in 2022, demonstrating the effectiveness of air quality management strategies already in place.

Water availability is also crucial to delivery of net zero and may be a limiting factor for development in parts of the HyNet industrial cluster. Catchment Abstraction Management Strategies (CAMS) and abstraction licence analysis indicate there is no further surface water or groundwater available in the Dee Catchment for consumptive use. The Weaver Dane and Lower Mersey may also have limited groundwater available. Surface water availability is likely to be greater north of the Mersey estuary and west towards Birkenhead. In other catchments surface water availability is highly dependent upon precise location.

Water quality will be an important factor in the authorisation of low carbon technology deployments. In the latest Water Framework Directive (WFD) investigations, the current surface and groundwater quality in HyNet is either 'Moderate' or 'Poor'.

The Mersey estuary has seen improvements in water quality since 1985, with the implementation of the 25-year Mersey Basin Campaign and investments by water companies, however the Mersey is still failing to meet the 'Good' ecological and chemical objectives set in the most recent River Basin Management Plan. Sources of pollution are varied, including industrial discharges, water industry effluent, agriculture, and navigation.

The impacts of climate change on water quality are complex, changes in water temperature and saline intrusion are two of the most significant issues facing freshwater ecosystems in the UK. In line with the rest of the UK, the Mersey estuary and surrounding river catchments are predicted to experience a rise in average water temperature.

Limited qualitative data on the likely wastewater discharges from planned developments within HyNet is a challenge to understanding potential impacts from discharges. Examples of wastewater arisings can include high salinity brine from hydrogen storage in salt caverns near Middlewich and acid scrubbing liquid waste from the carbon capture process that may impact nutrient (N), ammonia (NH_3) and new pollutants in rivers. Temperature of discharges will also be a factor in wastewater arisings adding to changes to surface water temperatures that will occur due to climate change.

The main findings of Phase 3 are:

1. **Low carbon technologies have the potential to emit previously unmonitored pollutants which may lead to air quality impacts.**

   Developers need actual baseline monitoring to understand how emissions may impact air quality locally. Some air quality monitoring is carried out by local authorities such as Redcar and Cleveland Borough Council, in Tees urban areas, measuring nitrogen dioxides NO_X and particulate matter $PM_{2.5}$, PM_{10}. Monitoring ammonia and amines in ambient air will help understand the contribution from low carbon technologies and target regulatory control.

2. **Current practice around the disclosure of emissions is likely to lead to a delay in capture plant operation.**

Developers submitting permit applications may choose to base their application on the use of a simple amine such as mono ethanolamine (MEA) to obtain their permit, though they may intend to use an alternative proprietary solvent at the point of commissioning. This would require a change to the permit, which could result in a delay to the operations of the capture plant.

3. **Later deployments of low carbon technology may face more significant challenges when combined impacts with earlier projects are taken into consideration.**

   Using the Teesside industrial cluster as an example, ecological sites such as the Coatham Dunes Site of Special Scientific Interest (SSSI), already exceed nutrient nitrogen levels due in part to emissions deposition from existing industry. In-combination assessments will likely present challenges to the permit determination of future projects. This will make assessing the impact of new applications harder to determine and may take longer.

4. **The amount of water available through direct abstraction is likely to reduce due to climate change.**

   Surface and groundwater availability may be a limiting factor for development around the south-west of the HyNet industrial cluster. Abstractions in this area are at high levels, with pending licence review changes; if developers plan to use non-public water supply from licences that are due to be reviewed, this may have unintended consequences for operations. But there is uncertainty now about which abstractors will be affected.

5. **Discharges from hydrogen production need further research to understand its cumulative impacts.**

   In HyNet uncertainty exists around wastewater discharges from low carbon technology and the potential thermal, toxicological and ecological impacts around catchments in the region. This is a risk regardless of whether wastewater discharges are direct to surface water receptors or indirect via the wastewater treatment network.

6. **Behaviour, policy, and climate change must be considered alongside development to manage water.**

   Clusters will undergo significant redevelopment that will require holistic consideration of low carbon technology developments. In the case of HyNet, the need for a sustainable supply of water and the capacity for wastewater treatment needs to also consider innovative reuse options for wastewater. An example of this could be the transfer of treated wastewater between low carbon projects on the Protos Park.

Work in Phase 2 emphasised that there are gaps in current knowledge that need to be addressed before scaling up deployment of low and zero carbon technologies. These gaps were still present during Phase 3. Industry needs to improve their understanding and response to environmental impacts of residual emissions from hydrogen and carbon capture. Understanding the cumulative impact of nitrogen dioxide emissions from hydrogen production and use on human health and habitats, as well as the impact of heat discharges from cooling processes on river and estuarine ecology and habitats. Industry must also forecast future climate conditions and build resilience into their plant designs.

As recommended in Phase 1, there is still a crucial role for industry to work together and to exchange information with the aim of developing combined plans and processes and to understand environmental capacity for industrial clusters. Industry, alongside national and local government have a strong leadership role to enable this. Information exchange with industry should include government agencies, local authorities, and utility companies.

2. Background

Low and zero carbon technologies are a vital part of our ambition to achieve net zero and limit the effects of climate change. Using this technology to prevent the emission of greenhouse gases are necessary. But they may also pose new risks to the environment and public health, particularly emerging technologies such as carbon capture and hydrogen production. These risks pose a potential challenge to government's intended target of deploying low and zero carbon technologies this decade.

Carbon capture and hydrogen production in English industrial clusters are the focus of this report. Each industrial cluster contains a diverse range of existing and proposed industrial sectors such as traditional heavy industries, varied types of power generation, petrochemicals, and chemical manufacture. There are large-scale plans for new low and zero carbon technologies such as carbon capture and hydrogen production and use. These aim to encourage the decarbonisation of existing industry and enable new developments that will not pose further risks to climate change.

Developments proposed by various projects will need to apply for and obtain appropriate authorisations under environmental and appropriate planning authorities to develop and operate. Planning and environmental permit applications will need to demonstrate that potential environmental impacts have been considered and technically assessed. Policy makers and regulators need to understand the extent to which these impacts will pose a challenge and ensure potentially negative impacts can be mitigated through the relevant planning and permitting statutory processes. They will need to understand how industry and leading stakeholders are preparing to address and manage them.

Water is an essential raw material required for carbon capture plants and hydrogen production. It is used in a variety of ways that can affect the environment; abstractions could be potentially limited. For example, water is used in carbon capture, for cooling purposes where much of the water is returned to the environment, but at a higher temperature that will need cooling before discharge. In addition, water is required for steam generation as the basis of the solvents used in the carbon capture process.

For hydrogen production, water usage varies according to the production method. Manufacture of hydrogen from methane has the lowest demand for water that is absorbed in the process (consumptive) and water that is needed for cooling that is returned to the water environment (non-consumptive). The most water intensive method for hydrogen generation is using electrolysis, with water as the feedstock. Water is 11% hydrogen, so at least 9 litres of clean water is needed to make 1kg of hydrogen. As very pure water is required, most available water feedstocks will need to be purified using a range of different technologies. It can be then split to make hydrogen. This means >20 litres per kg of hydrogen will be needed, for production and cooling, the majority of which becomes an effluent that requires appropriate disposal.

Extreme weather, flooding and periods of prolonged dry weather can significantly affect industrial assets and disrupt business operations. The level of disruption will depend, in part, on the resilience of sites and local infrastructure, including energy, transportation and telecoms. Planning policy requires decision-makers to apply tests that ensure people and property are safe from flooding so that developments remain operational for the asset lifetime. It should also ensure that new developments do not increase flood risk elsewhere. Emergency flood planning at sites at risk of flooding will help minimise the risk of pollution resulting from a flood event.

The work communicated in this report extends and builds on the preceding Phase 1 pathfinder project. Previous phases developed and trialled an approach to identify environmental capacity (focusing on water availability and water quality) of deploying carbon capture and hydrogen production in the Humber industrial cluster and a Phase 2 study that repeated a review of water availability and water quality in the Teesside industrial cluster whilst returning to the Humber industrial cluster to review the potential impacts of low carbon technology on air quality.

2.1. Project Objectives

This work aims to support government’s Net Zero Strategy and help to enable successful development of low carbon industrial clusters that are environmentally sustainable. By extending the project to include the HyNet industrial cluster the EA can further identify limits that the current and future environment will present, to inform working differently and mitigate environmental impacts, avoiding costly delays in technology deployment.

Our vision is that all industrial clusters explore their environmental impacts and challenges before designing and deploying low and zero carbon technologies. Derisking any potential negative impacts will benefit applications for planning and regulation, and the design and financing of the overall scheme, including associated infrastructure needs.

The main work objectives for Phase 3 of this project were to:

a. further develop the stakeholder engagement and evidence investigation approaches used in the Humber in Phase 1 and Teesside in Phase 2
b. investigate the environmental capacity of water availability and water quality in HyNet
c. investigate the environmental capacity of air quality and review emissions to air from proposed low and zero carbon technologies in Teesside
d. expand stakeholder engagement to include trade associations Hydrogen UK and the Hydrogen Energy Association and the non-departmental government organisations UK Health Security Agency and Natural England in HyNet and Teesside

In Phase 2 we covered flood risk as a challenge to the deployment of low and zero carbon technologies in the Humber industrial cluster. Following advice from local EA flood and coastal risk management teams it was decided not to include flood risk in future Phases of this work. This was due to the strength of evidence that already exists and awareness of this challenge, as well the expected similarities with Humber.

2.2. Role of the Environment Agency

Tackling the climate emergency is central to the work of the Environment Agency (EA). The EA Climate Ambition is to create a net zero nation that is resilient to climate change. Externally the EA is tackling climate change through regulation of industry, and by administrating the UK Emissions Trading Scheme. The EA also plays a critical role by helping communities to be better protected against climate impacts including rising sea levels and extreme weather events. We work with government, policy makers and developers to manage environmental risks at the earliest opportunity.

As the main environmental regulator in England, the EA regulate industry in industrial clusters and help industries prepare for necessary regulation. The EA regulate industrial and waste installations under the Environmental Permitting

Regulations (England and Wales) 2016 (EPR), and carbon markets under the UK Emissions Trading Scheme.

The EA is responsible for managing water resources in England, and the risk of flooding from main rivers, reservoirs, estuaries, and the sea. The EA safeguard water resources and ensure abstraction from surface and groundwaters do not damage the environment. By licensing water, the EA control the amount of abstraction to protect both water supplies and the environment under the Water Resources (Abstraction and Impounding) Regulations 2006. Soon to be brought under EPR.

The EA regulate emissions to air, land and water under EPR, ensuring that there is no deterioration in current water quality, as a minimum. Alongside the Health and Safety Executive, the EA is the competent authority under the Control of Major, Accidents and Hazards Regulations 2015 (COMAH). COMAH covers the storage of hydrogen, as well as other industrial processes.

The EA play an important role in enabling society to meet emissions targets through our regulation and advice in leading sectors, this includes industry, water, waste and agriculture. The EA have an important role in advising Local Planning Authorities on their decisions on new developments for matters within the EA remit, such as, flood risk, water resources, and water quality.

The EA work with others to share thinking about how low and zero carbon technologies and approaches may need to be regulated and the evidence needed to do this.

3. Project Methodology

3.1. Overview

The Phase 3 project team was made up of national and local area Environment Agency (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, create a literature review and develop and run the stakeholder engagement exercise. This helped us to understand the anticipated needs and environmental capacity of deploying low and zero carbon technologies directly from stakeholder groups.

3.2. Literature Review and Evidence Baseline

For the literature reviews, information was gathered on the following list of topics through a rapid review of available published literature with an agreed list of identified sources with our consultants. Where required, additional sources were suggested.

The Teesside literature review was broken down into four parts,

- emissions to air associated with grey and blue hydrogen production, and emissions associated with other hydrogen production
- possible hydrogen leakage rates at various production stages
- other emissions directly or indirectly associated with hydrogen production and use/ and carbon capture and storage (CCS), including nitrogen oxides (NO_x), nitrogen dioxide (NO_2), particulates (PM_{10}, $PM_{2.5}$), carbon monoxide (CO), carbon dioxide (CO_2), sulphur dioxide (SO_2), ammonia (NH_3), including degradation products, such as, nitrosamines and nitramines
- identifying gaps in evidence that may inform future research

The Teesside literature review assessed current evidence of potential emissions generated by hydrogen production and use. Search terms were used to perform the initial screening of literature related to net zero technologies and their associated effects on air quality and ecology. A review published reports and scientific papers was conducted through scientific databases, such as, Google Search, Google Scholar, Scopus, Science Direct and Web of Science. This method of reviewing significant amounts of information allowed a focussed literature search to provide a clear and objective analysis of existing literature on low and zero carbon technologies, focusing on significant findings and gaps in current research. This supported our aim to contribute to the knowledge in the potential effects of hydrogen as a sustainable fuel. For further information on the literature review please see Annex 1.

For the HyNet literature review the methodology was broken down into three separate parts,

- water requirements of the HyNet industrial cluster
- water availability in the HyNet region
- water quality and environmental risks in the HyNet region

To determine the water requirements of the HyNet north-west industrial cluster, existing reports relating to the water use of hydrogen production and the immediate available information around the extent of HyNet projects was reviewed. Gaps in knowledge were identified following the review of agreed literature and additional literature found through searching publication databases.

To determine the water quality status of the HyNet region, information on current water body Water Framework Directive (WFD) classifications, ‘Reasons for Not Achieving Good’ status (RNAG) and future objectives were taken from the EA

Catchment Data Explorer and the Natural Resources Wales (NRW) Water Watch Wales website. Further details on individual catchment water quality challenges were taken from the relevant River Basin Management Plans (RBMPs) and appropriate academic literature. A search of published literature was undertaken relating to designated sites, focusing on regional and local biodiversity and environment plans.

3.3. Stakeholder Engagement

Phase 3 continued and further developed the methodology developed in Phase 2. A communication and engagement plan was created to guide our engagement for the project. This step-by-step approach enabled teams in Teesside and HyNet to determine:

- what we wanted to achieve
- why we needed to engage with stakeholders
- who we needed to engage with internally and externally
- what engagement techniques should be used when engaging
- what went well and what could have been improved

A stakeholder analysis exercise ran in Teesside and HyNet to identify and prioritise engagement. In our initial analysis, the project identified over 200 stakeholders. The numbers increased as engagement started. As a project team we prioritised this extensive stakeholder list due to the short timescales for this work.

Phase 3 of the project focused on engaging with 5 stakeholder groups:

- internal (EA) experts for water, air and regulating industry
- industry including trade associations
- local planning authorities
- water companies and water resource organisations
- Natural Resources Wales, Natural England and the UK Health Security Agency

The project ran interactive workshops and individual meetings with industry, local authorities, and water companies, Natural England and Natural Resources Wales in the Teesside and HyNet industrial clusters. With local authorities, this included validating strategic growth assumptions against their own net zero strategies and presented opportunities for working together. Energy UK, Carbon Capture and Storage Association, Hydrogen UK and Hydrogen Energy Association were used to represent industry including the original equipment manufacturers (OEMs).

Internally, the project also developed and presented communications to help raise awareness of the project. This also helped us identify any potential links to similar projects. In addition, the project ran internal workshops with permitting and planning specialists.

As well as extensive engagement work, the project engaged with the Department for Energy Security and Net Zero (DESNZ) on communications planning and developed reactive lines to cover potential media interest.

We arranged online meetings with key stakeholders between December 2023 and March 2024. The meetings lasted 1 to 2 hours. Meetings with multiple stakeholders, such as, trade associations, regulators, local authorities, comprised a presentation by the EA, followed by an interview with questions adapted to the stakeholder(s). The smaller meetings with individual companies, for example, individual low carbon technology and OEMs, were conducted by the EA only and comprised a shorter presentation and interview.

Meetings were generally recorded, and a transcript was automatically generated. Summaries of each workshop and individual meetings were produced and used to inform the findings in this report. These are shared within Annexes 3 and 6 that accompany this report.

Stakeholders were chosen based on a review of stakeholder engagement exercises carried out in Phases 1 and 2 and the selection of new regionally specific groups, such as, water companies and water resources groups in HyNet. Organisations and trade associations included for the first time in Phase 3 were:

- UK Health Security Agency (UKHSA)
- Natural England (NE)
- Hydrogen UK
- Hydrogen Energy Association
- Original Equipment Manufacturers (OEM'S)

Overall, we conducted 17 workshops and meetings involving approximately 250 stakeholders.

Feedback was not part of the engagement work, we did however receive positive feedback, such as, stakeholders appreciated the opportunity to engage with us. Questions that could not be answered, or answered in full were taken away and sent back out to participants fully answered.

4. Evidence Evaluation

4.1 Overview

This section summarises the evidence presented in the technical annexes to explore the regional capacity of the environment to accommodate new demands on water supply and the ability of the air and water environment to absorb pollutants without negative impact. It considers demands on environmental resources and potential impacts on the environment from new low carbon developments, relating to air quality (Teesside) and water availability and water quality (HyNet). Further information can be found in Annexes 1-6.

4.2 Teesside Industrial Cluster

4.2.1 State of the environment

UK air quality continues to improve over time and air quality data collected in the Teesside industrial cluster mirrors this recovery. No Air Quality Management Areas (AQMAs) have been declared by the councils within the Teesside industrial cluster, reflecting the area's compliance with existing and proposed UK AQMS objectives. The primary environmental challenges in the Teesside industrial cluster are nutrients from existing direct discharges to the Tees estuary, and nitrogen deposition at the protected sand dune habitat.

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. (See Annex 2 for further information). A summary of air pollutants in the UK was initially released in 2012 and is updated each year with the latest annual statistics for six primary air pollutants: ammonia (NH_3), NMVOC's, NO_x, PM_{10}, $PM_{2.5}$ and SO_2.

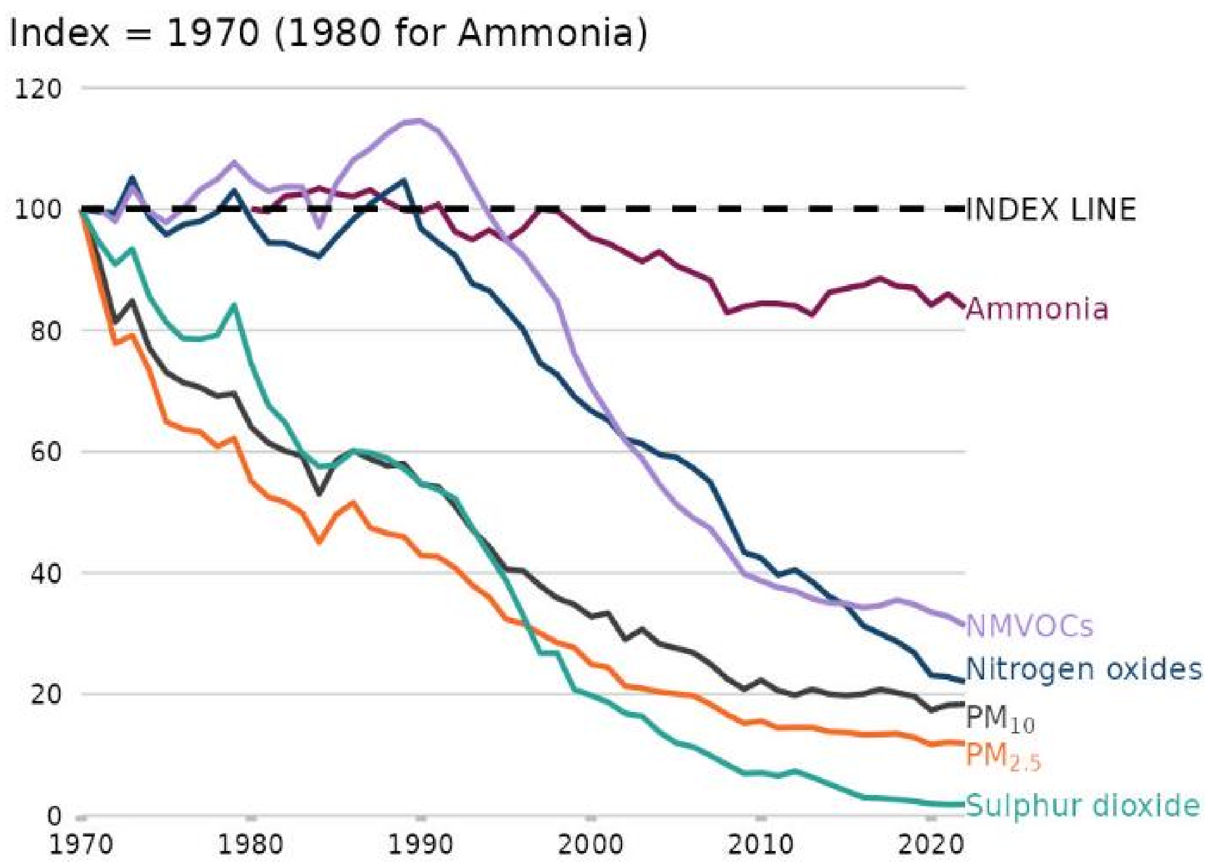

Figure 1: Summary of air pollutants in the UK from the February 2024 NAEI publication illustrates the long-term trends in UK emissions to air.

The index line in figure 1, illustrates annual emissions if they remained constant at 1970 levels while the y-axis represents the percentage of emissions against 1970 levels. There has been a clear reduction in atmospheric emissions for all six air pollutants since 1970 primarily due to tightening of emissions from power generation and road transport, and the phasing out of coal use.

Within the Teesside industrial cluster, the closure of the SSI steel works at Redcar in 2015 and ceasing coal use for steam generation at Wilton International, Redcar in 2016 resulted in significant reductions in the above primary pollutants emitted in the area.

The Teesside industrial cluster is characterised by industry, urban areas and protected habitats so opportunities to reduce agricultural NH_3 emissions are limited.

The Joint Nature Conservation Committee (JNCC) reported that in 2020 more than a third (36%) of UK land area (91,000 km^2) is sensitive to acidification, 38% (94,000 km^2) is sensitive to eutrophication, with many areas (72,000 km^2) sensitive to both. In 2020, acid deposition exceeded critical loads in 45% of sensitive terrestrial habitats and eutrophication exceeded critical loads in 86% of sensitive habitats. By 2022, most terrestrial areas exceeded the acid and nutrient nitrogen critical loads in the UK.

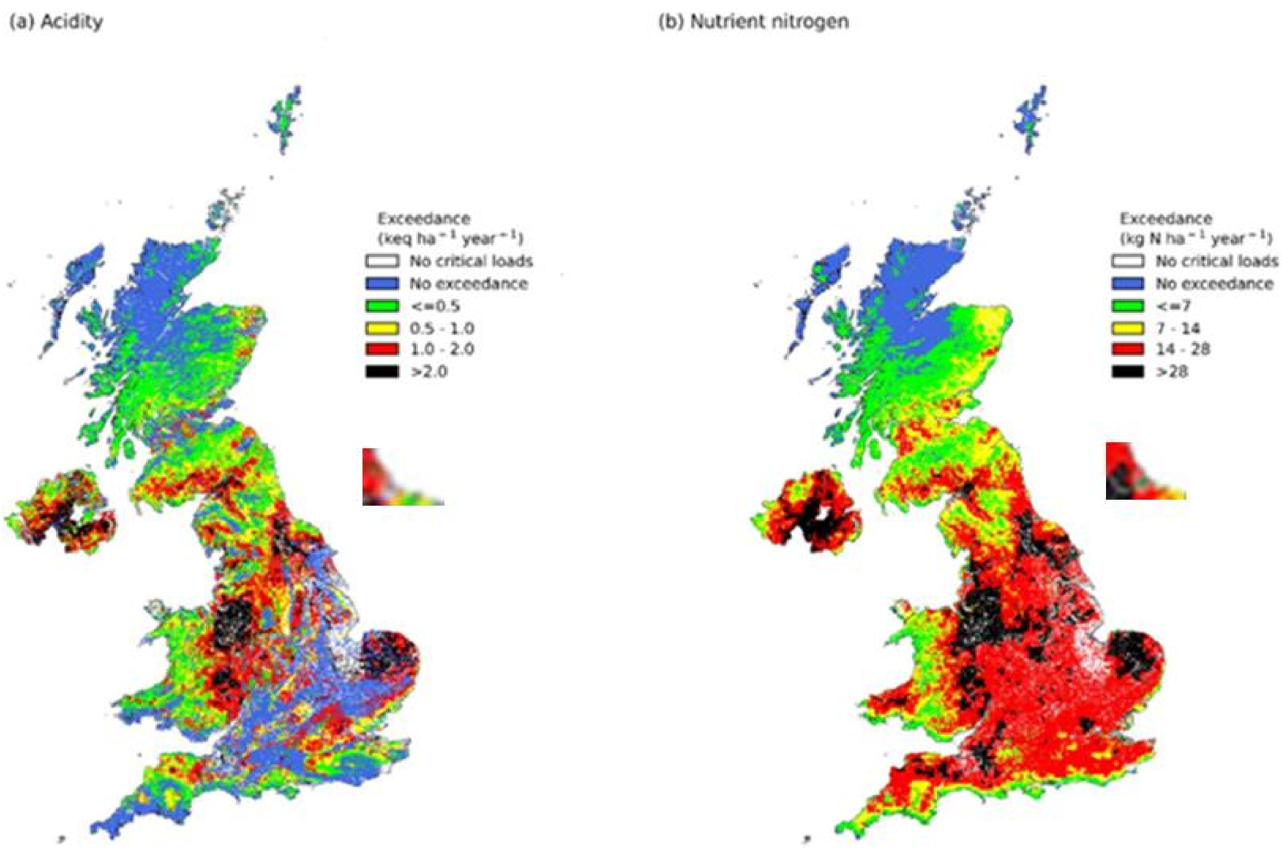

Figure 2: Acidity and Nutrient Nitrogen Critical Load Exceedances in the UK in 2022 (Defra, 2023) with map inserts showing close-up of the Tees industrial cluster area.

The maps in figure 2 show that the Teesside industrial cluster exceeds the higher thresholds for acidity and nutrient nitrogen critical load in 2022. NH_3 is the key pollutant contributing to nutrient nitrogen deposition and the UK sources are presented below.

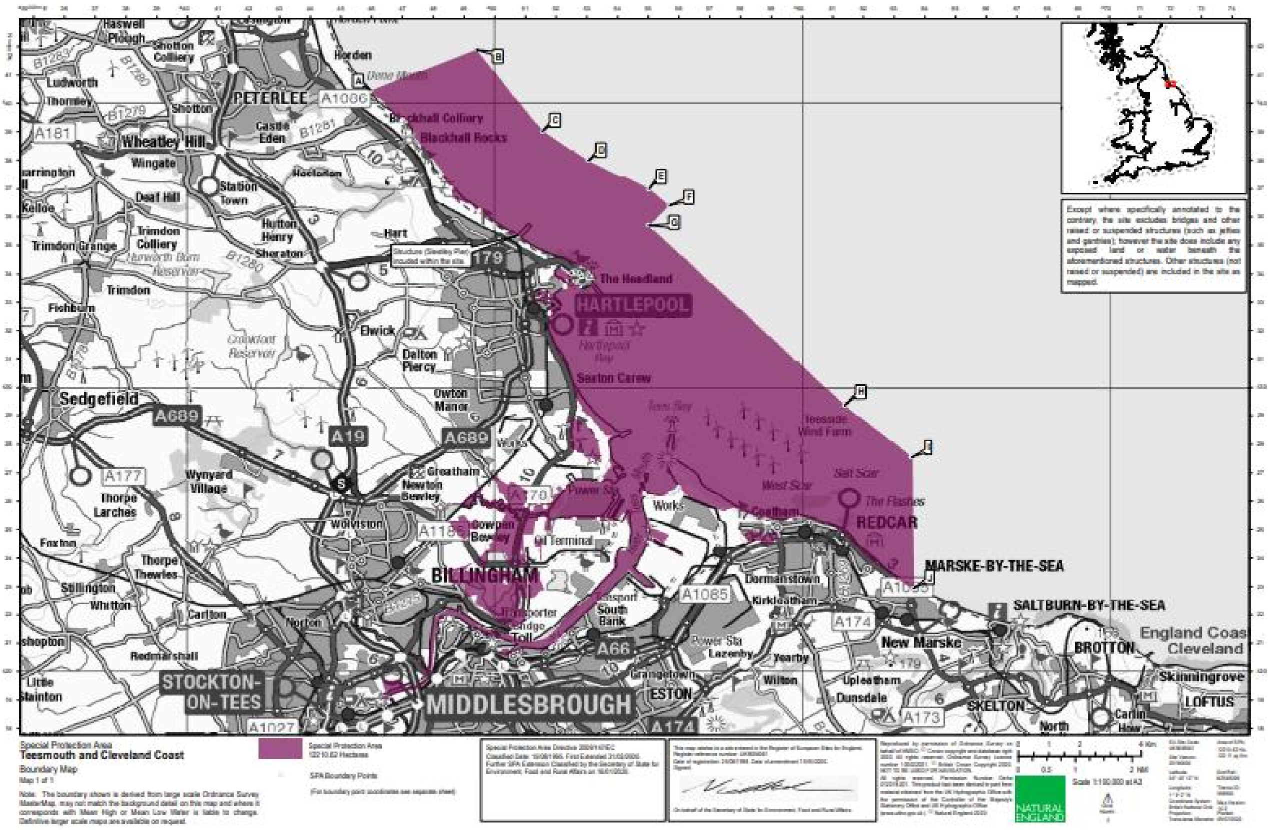

Figure 3: Co-location of Teesmouth and Cleveland Coast SPA and Teesside industrial cluster. Credit: Natural England.

Most ammonia pollution in the Tees originates from agricultural practices however, industrial emissions are not allowed to cause a deterioration of these protected habitats.

The Teesmouth and Cleveland Coast Special Protection Area (SPA) Site of Special Scientific Interest (SSSI) & Ramsar site surrounds a significant proportion of the industrial cluster.

Critical loads are habitat and feature-specific within the ecological site, reflecting the sensitivity and resilience of different ecosystems to pollutants. The lowest applicable critical load class within the Teesmouth and Cleveland Coast SPA is coastal dune grassland (calcareous type). This habitat type is found downwind of the Teesside industrial cluster and adjacent to the largest industrial redevelopment areas of Tees Works and Wilton International, at South Gare & Coatham Sands SSSI.

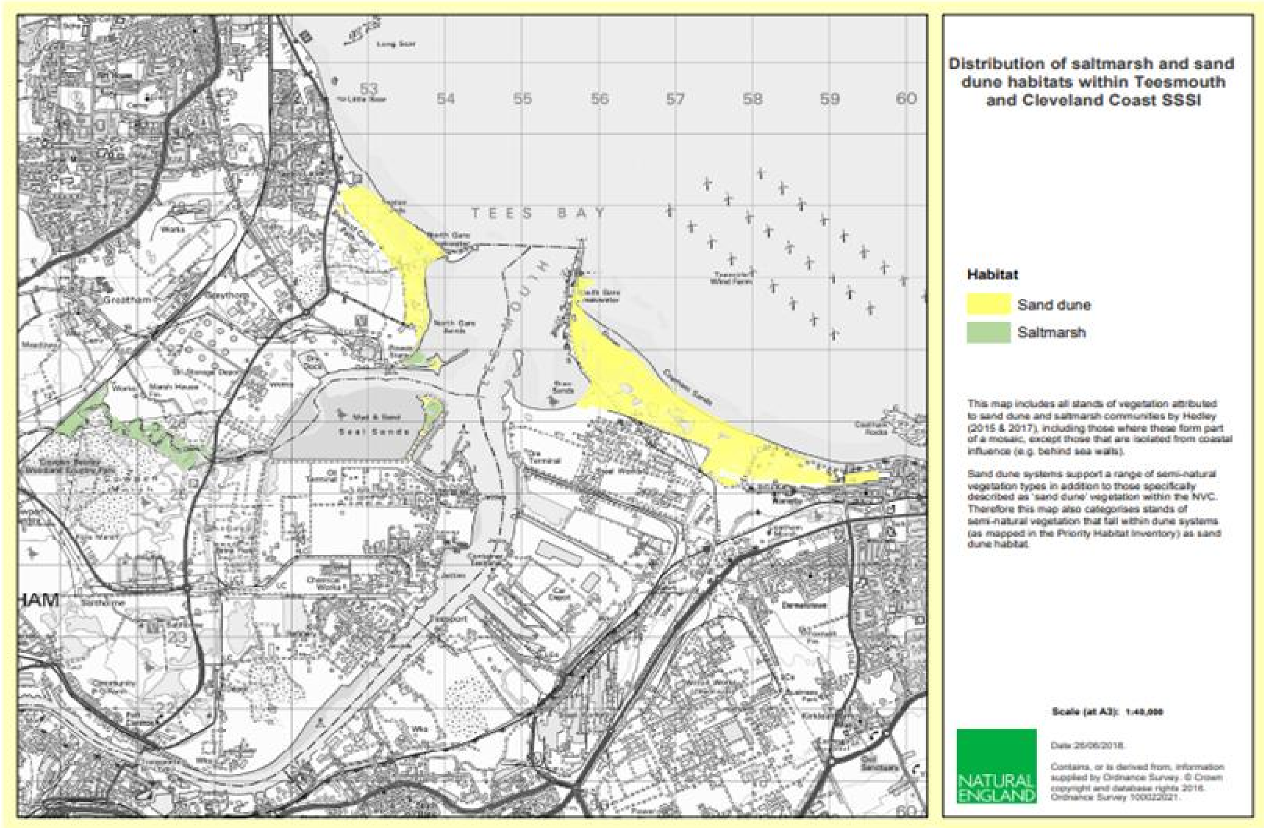

Figure 4: Sand dune habitat adjacent to the proposed industrial development areas.

The Teesmouth and Cleveland Coast SSSI includes extensive intertidal mud and sand, sand dunes, saltmarsh and freshwater marsh, established since the construction of the South Gare breakwater with tipped slag during the 1860s.

Figure 5: The South Gare & Coatham Sands SSSI sensitive sand dune habitat in the Tees Industrial Cluster. Credit: Alexander Ramsdale.

The largest source of total nitrogen impacting this habitat originates from livestock, fertiliser use and transport. Industry in the cluster have a variable impact on the local habitats and contribute more to sulphur deposition than nitrogen deposition.

Energy production and transformation processes, such as, electricity generation at power plants, the refining of crude oil into petroleum products, and the processing of natural gas, also contribute to both nitrogen and sulphur deposition but to a lesser extent than transportation, suggesting room for optimisation and control in all these sectors.

The common emissions from carbon capture, hydrogen production and hydrogen use are nitrogen dioxide, water vapour/ heat, and/ or particulates, ammonia, carbon capture solvent and solvent degradation products. These processes cannot significantly impact the local habitats by increasing nutrient nitrogen deposition.

Figures provided in Annex 2 illustrate the estimated background concentrations of key pollutants associated with industrial activities in the Tees area. These maps utilise data for 2023, which are projected based on actual emissions data and environmental conditions from a base year of 2018.

Figures provided in Annex 2 show a central zone at Tees Port for emissions of nitrogen dioxide (NO_2) and oxides of nitrogen (NO_x) from ships idling in port and a diffuse zone around Middlesbrough and Stockton relating to traffic emissions. Surrounding areas show notably lower concentrations including the industrial zones.

Figure 6 below shows the significant reduction in NOx and SOx emissions associated with the SSI Steel works and coal burning for steam and power at Wilton International, which had both ceased by 2016.

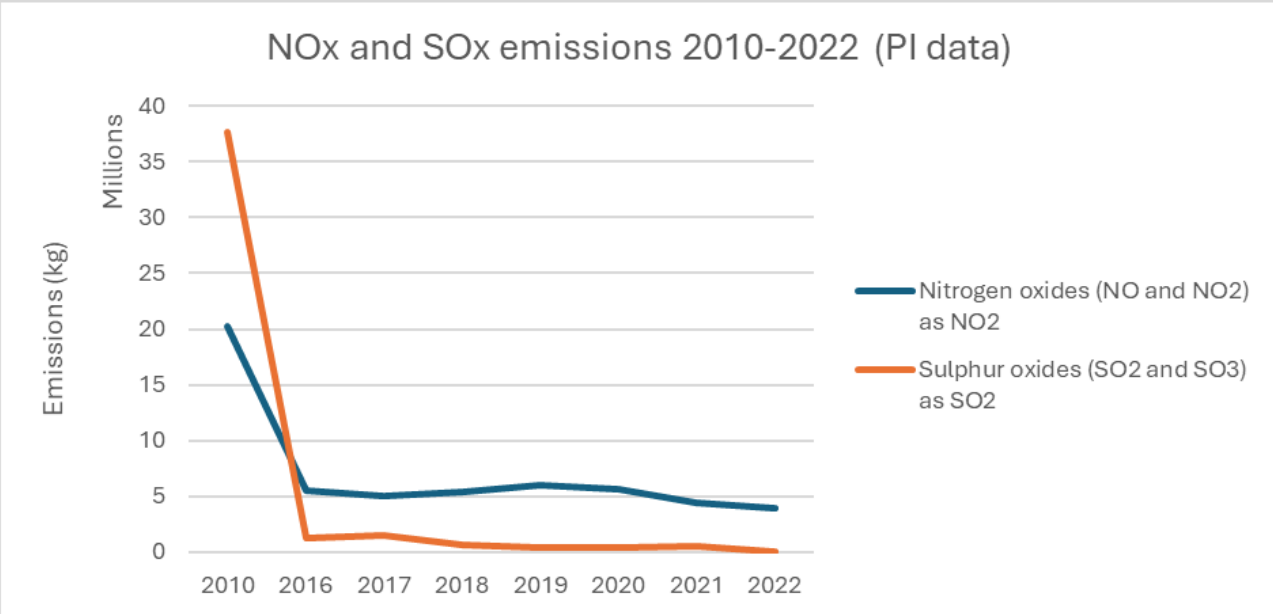

Figure 6: Reported Pollution Inventory data from industrial sources, 2013 to 2021.

Maps provided in Annex 2 show the distribution patterns for particulate (PM) with a diameter of 10 microns and 2.5 microns PM_{10} and $PM_{2.5}$ annual averages. Concentrations of PM_{10} and $PM_{2.5}$ are low and relatively consistent across the area with slightly raised levels of $PM_{2.5}$ concentrations along the A19 transport route, running north-south through Stockton-on-Tees. This uniformity across the geographical scope indicates a widespread dispersal of particulate matter with no significant increase within the Teesside industrial cluster area.

The main pressure on air quality in the industrial cluster can be attributed to emissions of NOx and PM from transport (road and shipping) and ammonia from agriculture, based on the narrow range of pollutants being regularly monitored. As the use of hydrogen fuelled vehicles and electric vehicle (EV) cars increases, these NOx and PM emissions are expected to decrease accordingly. New industrial projects, including carbon capture, hydrogen production and hydrogen use are predicted to emit a range of new pollutants, for example, degradation products from carbon capture solvents. A review of the current monitoring station locations and sampling regime is required, to ensure a complete description of future local air quality. Some pollutants not only influence local air quality but can also be transported over longer distances and can potentially affect air quality in adjacent regions.

4.2.2 Low carbon technologies and climate impact changes to the baseline

The Teesside industrial cluster is primarily an energy hub with access to oil and gas from the North Sea and a long industrial heritage involving chemical manufacturing.

Government investments and subsidies for low carbon technologies have changed the future of the industrial cluster with an increase in projects associated with carbon capture, hydrogen production and hydrogen use.

The cluster is considered geographically compact and its proximity to offshore carbon dioxide geological storage sites is strategically important. Water availability for industrial processes is less of an issue than other clusters due to construction of Kielder Water, the largest man-made reservoir in England, which started operations in the 1980s. It holds 200 billion litres of water, primarily to feed industry. Over 60 projects have announced their intent to decarbonise within the Teesside industrial cluster, of these, over 40 propose carbon capture, hydrogen production or hydrogen use.

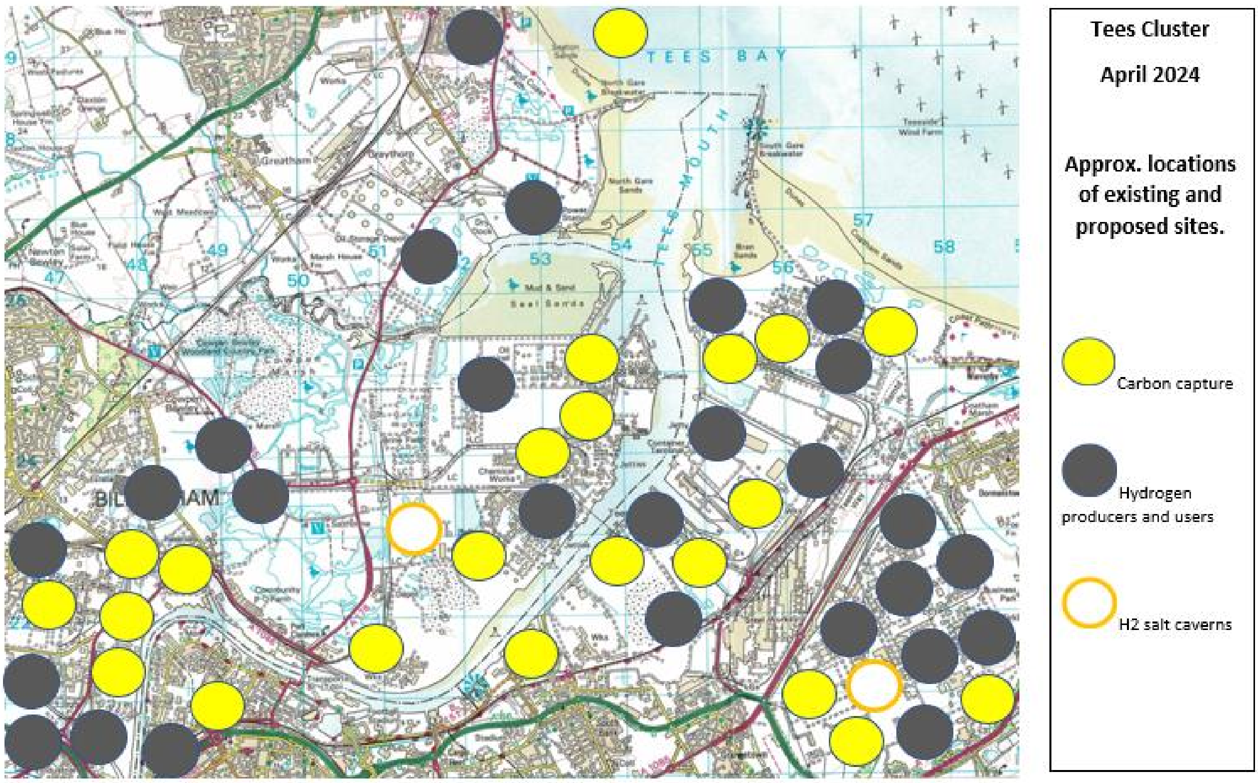

Figure 7: Map showing approximate location of existing and proposed carbon capture, hydrogen production and hydrogen use sites within the Teesside industrial cluster.

Many projects are concentrated within Wilton International and the Tees Freeport on the south side of the river Tees benefitting from tax relief and enhanced trade promotion. The majority of these will be new sites and will require new environmental permits to operate. Those on the north side of the river tend to be existing plants retrofitting carbon capture or hydrogen production and hydrogen use, with many requiring variations to existing environmental permits.

Low carbon technologies in Teesside

Net Zero Teesside (NZT) is a first-of-a-kind commercial scale gas-fired power and carbon capture project located in Redcar. NZT is a key driving force behind plans to install a Teesside-wide CO_2 gathering pipeline delivering captured CO_2 to the offshore Endurance geological storage facility. NZT have secured early engagement of several industrial, power and hydrogen production processes within the Teesside industrial cluster, to feed into the proposed CO_2 gathering pipeline.

To date, at least £195 million of government funding has been allocated to carbon capture, hydrogen production and hydrogen use projects in the Teesside industrial cluster demonstrating the significance of this area within the UK's net zero plans.

The range of proposed carbon capture projects within the Teesside industrial cluster can be found in Annex 2.

The Teesside industrial cluster is expanding the range of industrial uses for captured CO_2:

- recent significant government funding is supporting several large-scale Sustainable Aviation Fuels (SAF) production projects which propose combining locally produced green hydrogen and industrially captured CO_2 to produce SAF
- food and drink sector, for example carbonated drinks, abattoirs and food packaging

Hydrogen can be generated at an industrial scale in several ways and the resulting hydrogen, while chemically the same, is named differently depending on how it is generated (National Grid, 2023). Annex 1 describes the different types of hydrogen production that were reviewed in this study. Several hydrogen production processes already exist or are being proposed in the industrial cluster. The range of existing and proposed hydrogen production and use projects can be found in Annex 2.

Initially, the use of hydrogen was expected to be prioritised within hard-to-reach or heavy industry, however discussions with stakeholders revealed that many natural gas users within the industrial cluster are considering fuel switching to blends of hydrogen due to their desire to decarbonise. Fuel switching take-up is partially dependent on the demonstration of a robust supply of hydrogen which is expected to be achieved once the Teesside CO_2 gathering pipeline becomes operational and the large-scale blue hydrogen plants commence operation.

The development of large-scale hydrogen storage is considered essential to enable the predicted significant increase of hydrogen use. The Teesside industrial cluster benefits from two existing salt cavern storage facilities which are being considered for expansion to cope with predicted demand. PD Ports, one of the UK's major port operators, are actively reducing their carbon footprint and foresee the need to increase their ammonia bulk storage facility for maritime use.

Fuels, such as hydrogen, may help reduce carbon emissions, however this depends on how the fuel is converted into energy which could potentially lead to worsening air quality (UKHSA, 2023). The production of green hydrogen, especially from low-carbon energy sources, has been linked to potential health benefits. A study (Raouf,

2023) suggests that the production and use of green hydrogen not only contributes to environmental sustainability but also has positive implications for public health, financing, and outcomes. Reducing CO_2 emissions through increased use of hydrogen energy can help countries allocate more resources to public health, highlighting the interconnectedness of energy policy, environmental health, and public health expenditure (Raouf, 2023).

Whatever the type or colour, hydrogen production has its distinct environmental footprint and technological requirements. For example, green hydrogen production, which uses renewable electricity, offers zero direct CO_2 emissions, setting it apart from its counterparts (Ishaq et al., 2022). Green hydrogen production is more electricity-intensive and water-intensive, compared to other low CO_2 hydrogen production technologies and requires over 37 times more power than the conventional steam methane reforming (SMR) process when combined with carbon capture and storage (CCS). (Hristescu, 2022) [20].

The potential environmental impact of green hydrogen production is linked to the electricity source used for powering electrolysers. A potential impact occurs when dealing with irregular renewable energy sources like wind or solar, which may require adjustments in operating hours to optimise renewable electricity use or a back-up grid connection. The efficiency of the conversion process, the capacity hours when using irregular renewable energy sources, and the critical need for grid inputs, potentially from the closest source, such as a natural gas-fired power station, are identified as critical factors. These will significantly affect both the efficiency and the environmental sustainability of green hydrogen production (Vilbergsson et al, 2023).

Blue hydrogen is increasingly viewed as a transitional energy carrier in the move towards a low carbon economy. But production and environmental impact of blue hydrogen is subject to various factors that influence its overall carbon balance and efficiency. EA (2021) European site protected areas: challenges for the water environment discusses various technologies associated with blue hydrogen production; these are summarised in Annex 1.

As stated in Annex 1, Howarth and Jacobson, 2021 indicate that the greenhouse gas footprint of blue hydrogen is over 20% greater than directly using natural gas or coal for heating. However, Romano et al. (2022) point out that the methane leakage rates used by Howarth and Jacobson are higher than observed in many countries and can be reduced using existing technologies at low costs. They conclude that for blue hydrogen to play a role in transitioning to a decarbonised economy, it must achieve significantly lower greenhouse gas emissions than the direct use of natural gas.

For blue hydrogen to meaningfully contribute to reducing greenhouse gas emissions, natural gas leakage rates throughout the supply chain must be addressed. The latest understanding of upstream natural gas leakage suggests a range of 1% (best case) to 3% (worst case) per unit of methane consumed.

Similarly, the downstream uses of captured CO_2 must be managed to prevent re-release into the environment.

The greenhouse gas emissions associated with blue hydrogen production are varied. The highest emissions are observed in the blue hydrogen method of steam methane reforming without CCS, while the lowest are in auto thermal reforming with CCS. A study by (Wang et al, 2007) and (Wang et al, 2008), concludes that all hydrogen pathways, particularly steam methane reforming have a low impact on air pollution. With centralised pipeline delivery to hydrogen users being the most effective in minimising pollution, followed by on-site production.

Along with the concern of natural gas leakage rates in the blue hydrogen supply chain, a key consideration is the impact hydrogen leakage may have in terms of climate change. While increased hydrogen use could lead to reductions in methane (CH_4), CO, NO_x, and volatile organic compounds (VOCs) (Warwick et al., 2022), concerns exist about hydrogen leakage regardless of its production method. This is due to the smaller molecule size of hydrogen, in comparison to natural gas, leading to potentially higher leakage rates from pipelines, storage tanks, and connections.

Across the entire hydrogen supply chain, leakage rates vary widely based on system design and operational practices, with overall estimates ranging from a fraction of a percent to as high as 10-20%.

Using hydrogen, either by adding hydrogen to natural gas or pure hydrogen burning, significantly reduces the level of CO_2, and it reduces to zero when pure hydrogen is used (Topolski et al, 2022). Hydrogen can help reduce carbon emissions but how fuel is converted to energy needs to be considered to avoid worsening air quality.

Annex 1 refers to recent investigations into the use of hydrogen as a combustion fuel that indicate a complex relationship between hydrogen enrichment and NO_x emissions. While hydrogen's higher flame temperatures and laminar flame speeds have the potential to increase NO_x emissions significantly when compared to conventional fuels, this effect can be influenced by the type of combustion application and burner design (Dunphy, 2023; Limpsfield, 2023). When burning hydrogen, it is predicted that the mass emissions of NOx remain the same when compared to natural gas, however, the removal of CO_2 from the flue gas increases the volumetric emission rate. New emission limit values for a range of natural gas and hydrogen blends, up to 100% hydrogen, has been developed by the Environment Agency in consultation with trade associations, industry and OEMs.

Carbon capture technologies will be heavily relied upon within the Teesside industrial cluster to remove CO_2 from a wide variety of industrial processes. It is one of the significant contributions to decarbonisation ambitions from the cluster and will be developed on technologies that were originally designed to improve the quality of emissions from natural gas.

The British Steel initiative for constructing a new electric arc furnace (EAF) at Lackenby in Redcar for steel production, using hydrogen fuel and carbon capture technologies, significantly minimises carbon emissions from the iron and steel sector. However, it is important to note that the pre-heat phase of the EAF processes has been identified as a source of polychlorinated biphenyls (PCBs) emissions into the air, an environmental concern that requires attention alongside greenhouse gas management.

Anaerobic Digestion (AD) plants promote sustainability in waste management, carbon sequestration and dry AD treatment of organic waste. The environmental profiles of bioethanol and biogas can be improved by using carbon capture and discussions have started with two Teesside operators to consider discharging planned captured carbon into the Teesside-wide CO_2 gathering pipeline.

Examples of existing carbon capture and hydrogen use in the industrial cluster include the production of bioethanol with CO_2 capture at Ensus and SABIC's reuse of hydrogen produced during the cracking process as a fuel, offsetting their ongoing use of natural gas. These large-scale processes are often used as good examples of how operators can reduce the carbon footprint from chemicals manufacturing.

A key component of carbon capture is the use of amines in the capture solvent and the potential increase in environmental and health risks. The low carbon technologies proposed for the Teesside industrial cluster require approximately 20 different carbon capture processes, potentially 20 different carbon capture solvents, optimised for each process. Direct emissions of amines and their degradation products can be released into the air during the carbon capture process. Additionally, these substances can react to form harmful compounds, such as nitrosamines and nitramines. In future, as the carbon capture technology matures, solvents may not be based on amines to reduce these impacts. Given the complex and varied behaviour of the proposed amine-based CO_2 capture solvents, a comprehensive, independent assessment of the emissions, their destination and behaviour in air and water is required. This work would ensure a broader understanding of their potential impacts while acknowledging that individual amines like monoethanolamine (MEA) or diethanolamine (DEA) may have specific characteristics and effects. A comprehensive view would avoid oversimplifying and better account for the nuanced environmental interactions of amines. Amine-based carbon capture technologies, while effective in mitigating climate change through CO_2 emission reduction, present environmental and health challenges due to the potential formation and release of toxic N-amines, including nitrosamines and nitramines, known for potential health risks, (Nielsen et al, 2012; Spietz et al, 2017; NEA, 2022; AECOM, 2017) as known carcinogens. For a full-scale gas-fired power plant capturing 1 million tonnes of CO_2 per year, the estimated amine emissions range from 40 to 160 tonnes per year (Knusden, 2009).

Climate impacts

Annex 1 describes the full range of emerging carbon capture solvents, each offering unique benefits. The potential for exacerbated air quality issues due to climate change, rising temperatures and changing precipitation patterns threatens to affect vulnerable populations and ecosystems. Various climate conditions, especially temperature and humidity, have the potential to affect the performance of solvent-based systems, including carbon capture technologies. CO_2 capture rate is significantly influenced by air temperature and relative humidity. A study by (An et al, 2022) found that high CO_2 capture rates (up to 85%) are achievable in hot and humid climate conditions, whereas the capture rate drops dramatically in cooler and drier conditions. For example, a CO_2 capture rate of 75% is only possible above 17°C and 90% relative humidity. Met Office maximum temperatures for the 30-year period 1991-2020 at Hartburn Grange, Stockton show temperatures above 17°C for only four months of the year, June – September. Global warming is expected to bring prolonged periods of extreme temperatures which may result in variable CO_2 capture rates. The energy demand and the cost of CO_2 removal are strongly impacted by varying CO_2 capture rates, which are influenced by climate conditions. The study observed that the overall energy demand decreases as the CO_2 capture rate increases. It also noted that the cost of capture could vary significantly based on climate conditions, being more sensitive to temperature than to relative humidity.

The studies highlighted the need for deployment strategies to consider specific climate conditions, as they greatly influence the system's efficiency and operational costs, suggesting that this is crucial for optimising the efficiency and cost-effectiveness of these systems in different climatic environments.

In combustion plants, higher ambient temperatures can affect the cooling efficiency of the plant. Cooling systems, which are essential for maintaining optimal operating temperatures, become less efficient in warmer conditions. (Petrakopoulou et al, 2020) investigated how rising ambient temperatures affect the performance and water use of natural gas and coal power plants and highlighted those higher ambient temperatures led to increased pressure at the steam turbine outlet, thus decreasing plant efficiency.

In the hierarchy of best available cooling techniques for nuclear and combustion plants, sea water is the preferred option for maximum efficiency with warmed cooling water returning to the sea but not consumed by the process. As sea temperatures rise, this preferred option will become less effective and impact the efficiency of power plants. Alternative large-scale cooling methods use more electricity to power the process and partially consume the raw water, resulting in releases of steam, which warm the atmosphere.

Warmer weather can also impact amine regeneration in carbon capture technologies. Amine regeneration, the process of releasing absorbed CO_2 from the amine solvent, is typically an energy-intensive thermal process. Increased ambient temperatures can influence the thermal dynamics of the regeneration process.

The thermal degradation of amines is an important factor in limiting the temperature and pressure in amine regeneration. By understanding the different degradation processes, amine regeneration can be optimised, and operational temperatures can be balanced to minimise degradation while maintaining efficiency. (Rochelle et al, 2012, Hong et al, 2020) examined how different amines (MEA - monoethanolamine, DEA - diethanolamine, MDEA - methyldiethanolamine, AMP – 2-amino-2-methyl-1-propanol) behave under various temperatures and provided insights into optimising amine regeneration at lower temperatures.

Air quality and health impacts

Annex 1 considers the available evidence for the human health effects of carbon capture, hydrogen production and hydrogen use. The health and environmental impacts of carbon capture technologies, particularly those involving amine-based scrubbing solvents, as well as the potential effects of hydrogen use, have been the subject of various studies. These impacts are critical to understand as the use of these technologies' increases, in efforts to mitigate climate change.

The Health Effects of Climate Change (HECC) report emphasises the health benefits of transitioning to low carbon energy sources, like green hydrogen, which can lead to improvements in air quality and, consequently, public health outcomes. Specifically, it notes the potential health benefits of reducing $PM_{2.5}$ and NO_2 exposure through climate change mitigation measures and the transition to renewable energy sources, including the implications of these transitions for reducing greenhouse gas emissions and improving public health. $PM_{2.5}$ and NO_2 levels are below current air quality standards within the Tees Industrial Cluster and these pollutants are expected to reduce further as the use of electric and hydrogen fuel cell vehicles increases. A robust supply of locally produced hydrogen, coupled with Government funding for the Tees Valley Hydrogen Transport Hub providing publicly accessible hydrogen fuelling stations for HGVs, buses, vans and emergency vehicles, will enable a faster transition to low carbon transportation.

(Zoback and Smit, 2023) in their study, explored the environmental and health impacts of large-scale carbon capture and hydrogen production, suggesting that the safest and most practical strategy for dramatically increasing CO_2 storage in the subsurface is to focus on regions with multiple partially depleted oil and gas reservoirs. This approach, coupled with large-scale hydrogen production, presents an economically viable strategy for reducing greenhouse gas emissions. The study suggests that understanding and mitigating any potential health risks from such large-scale operations are crucial for ensuring the safety and health of populations in oil and gas producing countries.

While amine-based carbon capture technologies show promise for reducing CO_2 emissions, they also present potential risks to human health and the environment, primarily due to the emissions of amines and their degradation products, including nitrosamines and nitramines. The Sustainable Operation of Post Combustion Carbon Capture (SCOPE) project report (Lathouri et al, 2022) explains the health risks posed by nitrosamines and nitramines, emphasising their carcinogenic potential. It covers toxicological data, environmental guidelines, and the need for strict measures to mitigate risks from these compounds. Special attention is given to sensitive populations like children, highlighting their increased vulnerability to these substances.

The report emphasises comprehensive monitoring and control measures to manage exposure via air, water, or occupational contact. Findings in the report highlight the importance of rigorous safety standards and continuous monitoring to protect public health around carbon capture plants, particularly for vulnerable groups like children, who face a higher risk of cancer from exposure to these chemicals.

The government's Industrial Decarbonisation Strategy (2021) states that the Teesside industrial cluster stands at a critical moment, balancing industrial innovation with environmental stewardship. As it begins a transformative journey toward decarbonisation, integrating pioneering low carbon technologies, the industrial cluster faces a complex matrix of promise and challenge.

To understand current air quality and future environmental impacts in Teesside, a comprehensive environmental monitoring framework is needed. Such a framework should not only facilitate the strategic assessment and management of cumulative air quality impacts but also support the cluster's ambitious industrial development while preserving ecological integrity. This includes:

- detailed studies on the lifecycle environmental impacts of hydrogen production and use, particularly regarding water demand, NOx emissions and potential leakage
- long-term assessments of the effectiveness and environmental impacts of carbon capture technologies, focusing on amine emissions and their degradation products
- continuous monitoring and modelling to refine projections of air quality and ecological health within the cluster, informed by real-time data and technological advancements
- rigorous research into the known unknowns of carbon capture technologies and the environmental impacts of different hydrogen production methods to inform adaptive policymaking and stakeholder engagement

4.3 HyNet Industrial Cluster

4.3.1 State of the environment

The HyNet industrial cluster extends across multiple river catchments and crosses the England-Wales border. The industrial cluster is in an area with important national heritage and numerous protected sites, such as SSSIs and SACs, including some internationally important sites (Environment Agency, 2013; Environment Agency, 2020a).

Figure 8: View north-west towards the HyNet area and Ellesmere Port.

Several habitat-specific protection sites exist within the area. Both the Mersey and Dee estuaries contain SSSI, RAMSAR and SPA sites, with the Dee estuary also classed as a SAC (Figure 9). The SPA status reflects the estuaries' importance to sea birds and wildfowl including little tern, red-throated diver and whooper swan, river lamprey and sea lamprey (Environment Agency, 2022, Defra, 2021). They are also important for smelt, eel, trout and salmon, and are breeding grounds for commercially important fish species. If HyNet developments have the potential to impact SAC, SPA or RAMSAR sites, a habitat regulations assessment (HRA) will be needed to ensure that appropriate mitigation and protection measures are implemented.

The assets close to the Mersey estuary will need to carefully consider wastewater discharge quality if there is an intention to discharge into the Mersey estuary or be encouraged to connect to the public sewer network if reasonable to do so.

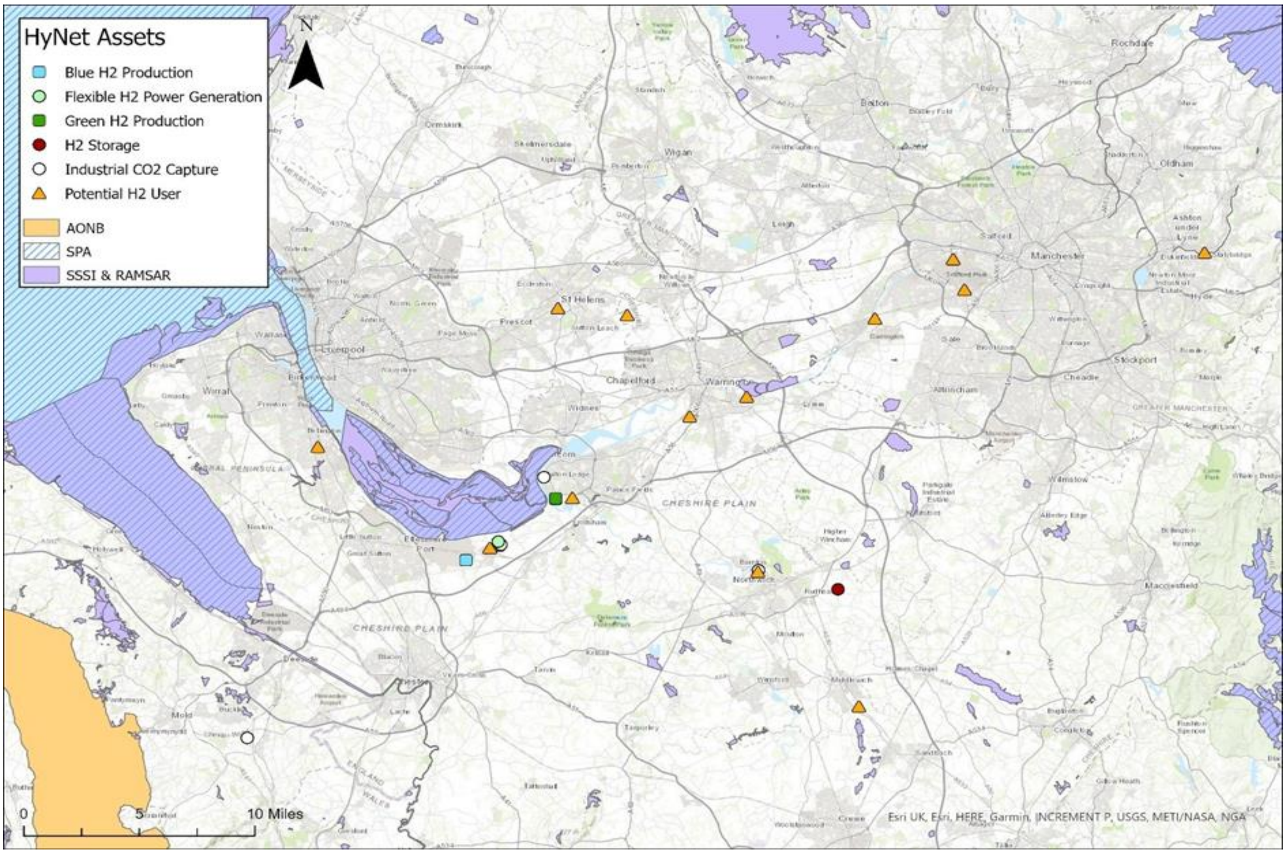

Figure 9: AONB, SPA, SSSI, and RAMSAR sites in HyNet NW area.

South of the River Mersey is low lying countryside interspersed with heavily industrialised areas, though most of the industry is clustered along the Mersey estuary and urban areas (Environment Agency, 2023b), agriculture is prominent in this area, especially dairy farming (Environment Agency, 2013). Industries include power/ energy, chemical, paper, and a history of salt mining (Environment Agency, 2020a). To the north and east of the Mersey, land use includes both rural and heavily urbanised areas.

The Lower Mersey abstraction licensing catchment south of the Mersey estuary is the most notable area of concern regarding water availability. HyNet assets in this location will be vulnerable to limited or no water available at low flows (Environment Agency, 2013).

The average supply for United Utilities Strategic Water Resource Zone (WRZ) is 1794 Ml/d, serving a population of around 7.17 million (United Utilities, 2023). This Water Resource Zone (WRZ) is surface water dominated with some local groundwater sources, such as the groundwater abstraction boreholes in Mersey and Bollin catchments. For the entire region served by the water company United Utilities (UU), 94% of the water supplied comes from river or reservoir sources, and 6% comes from groundwater. This balance may vary slightly in a dry year. Private water supplies in the HyNet region are dominated by navigation requirements, industrial abstraction and, to a lesser extent, agriculture (Environment Agency, 2013).

The Dee Catchment Abstraction Management Strategy indicates that there is no surface water available within the Dee abstraction management catchment for consumptive use, suggesting water trading as an option to get surface water from the River Dee (Natural Resources Wales, 2015).

The Mersey estuary is vulnerable to water quality issues because of industry discharges and wastewater effluents from urban sources. The Mersey estuary has seen improvement in water quality since 1985, due to the 25 year ‘Mersey Basin Campaign’ (Source magazine, 2023) and substantial previous investments by UU. The Mersey estuary is still failing to meet the ‘good’ ecological and chemical objectives set in the most recent River Basin Management Plan (RBMP).01

The current Water Framework Directive (WFD) classifications for the groundwater bodies surrounding the HyNet industrial cluster are classified as ‘poor’ due to chemical failures (nitrates, pesticides, and other chemicals) and chemical-dependent surface water bodies. Some of the groundwater contamination can be put down to surrounding agricultural and rural land management, with further investigations still ongoing. For further detail on groundwater WFD classifications, Reasons for Not Achieving Good water quality (RNAG), and objectives, see Annex 4.

Diffuse source contamination from nearby industry is contributing to high concentrations of zinc and tributyltin compounds within the estuarine sediment and associated catchment land. The presence of benzo(g-h-i) perylene, polybrominated diphenyl ethers (PBDE) and mercury compounds within the Mersey estuary also contribute to the failed chemical status. From an ecological perspective, the waterbody remains unsatisfactory for invertebrates and phytoplankton, with high levels of dissolved inorganic nitrogen.

The Manchester Ship Canal has a current WFD classification of ‘moderate’. Sewerage discharge, landfill leaching and pollution from the navigation industry are all contributing to failing levels of tributyltin compounds. In addition to these pollutant sources, mercury compounds and Polybrominated diphenyl ethers (PBDEs) are contributing to the chemical failure of the waterbody, although the source of this pollution has not been attributed to a specific industry sector.

The Wirral and West Cheshire Permo-Triassic Sandstone Aquifers, the Weaver and Dane Quaternary Sand and Gravel Aquifers, the Lower Mersey Basin and North Merseyside Permo-Triassic Sandstone, Aquifers, and the Dee Permo-Triassic Sandstone are all failing to meet ‘good’ WFD standards. The reasons for the ‘poor’ groundwater body classifications are generally associated with chemical tests, chemical drinking water protected area legislation, and saline intrusion. The source of these failures has been attributed to poor pesticide and nutrient management in the agricultural industry, along with some failures from the water industry and other stakeholders.

Current challenges to water resources and water quality will have consequences to ecologically sensitive sites including designated habitat sites. The presence of protected areas/designations may limit what activities can occur. Permits that affect the environment, including water abstractions and wastewater discharges, are less likely to be issued permits, those that are issued may have tighter conditions (Environment Agency, 2010).

The UK government’s 25 Year Environment Plan sets out the ambition to restore 75% of terrestrial and freshwater protected sites to favourable condition, providing an example of the direction in which the protection of ecologically sensitive sites is heading (Environment Agency, 2021).

Planned low carbon technology projects around the Mersey estuary may have tight limits imposed on their permits on wastewater discharge, should they wish to directly discharge to surface water, or encouraged to connect to the public foul sewer wherever possible.

A significant proportion of HyNet is within nitrate vulnerable zones (NVZs). These are designated areas that are at risk from agricultural nitrate pollution. Whilst their presence doesn’t directly relate to development, developers should be aware of their presence, especially with respect to hydrogen production and carbon capture that release nitrogen oxide in wastewater. Eutrophic rivers are also present within these NVZs. One proposed carbon capture location is close to a eutrophic river. Two hydrogen users are also close to eutrophic rivers.

Nutrient assessments may be necessary for developments to ensure that new processes do not result in an increase of nutrients entering a waterbody. This is to reduce the likelihood of harmful impacts of increased nutrients, such as eutrophication focussing on nitrogen and phosphorus. The nutrient assessments are carried out as part of the Habitat Regulatory Assessment (HRA) in areas where there are unfavourable levels of nitrogen and phosphorus.

Natural England and NRW have indicated that developments near to four SACs in the north-west and north Wales require nutrient assessments (Rankl., F., 2023). The SACs in question are shown in Table 1.

Special Area of Conservation (SAC)	Statutory nature conservation body	Neutrality driver
Oak Mere	Natural England	Phosphorus
Rostherne Mere	Natural England	Nitrogen and Phosphorus
West Midlands Mosses	Natural England	Nitrogen and Phosphorus
River Dee and Bala Lake (Wales)	NRW	Phosphorus

Table 1 Summary of SACs requiring nutrient assessments near to HyNet NW.

4.3.2 Low carbon technology and climate impact changes to the baseline

The HyNet north-west industrial cluster is a planned network of new and existing infrastructure that will capture carbon, and produce, transport and store hydrogen in north-west England and north-east Wales for industrial hydrogen users. Progressive Energy is a coordinating partner of a consortium of companies responsible for the development.

It is currently known to comprise four hydrogen production projects, six carbon capture projects and hydrogen storage. These are predominantly located in Cheshire between Ellesmere Port and Runcorn, south of the Mersey estuary and Manchester Ship Canal. HyNet extends across the English-Welsh border into north-east Wales, however, the focus of this work is within the English region. The number of projects is likely to vary as the carbon dioxide and hydrogen pipeline infrastructure is developed, particularly to provide conversion of boilers to hydrogen by industrial end users. During our industry stakeholder engagement, the Environment Agency were advised that some of these also plan to become producers.

Hydrogen production and carbon capture and storage is the focus of this review, but it is recognised that they are part of a range of projects in the cluster, including fuel switching, hydrogen storage in salt caverns, large scale battery energy storage, and sustainable aviation fuel production (SAF).

The largest hydrogen production development in HyNet is the EET Fuels blue hydrogen project at Stanlow refinery, Ellesmere Port, Cheshire. The initial phase of hydrogen production for fuel switching and carbon capture and storage is currently consented and will consist of reforming of natural gas and refinery off-gas, together with carbon capture and storage and commonly referred to as blue hydrogen. This process involves natural gas and refinery gas being heated, subjected to purification and water saturation process, passed through reformers to produce a syngas, before being subjected to a catalyst that promotes a reaction to produce hydrogen and carbon dioxide.

A further phase of blue hydrogen production is planned together with development of green hydrogen production. The first phase known as Hydrogen Production Plant 1 (HPP1) is planned to generate 3 TWh per year (equating to 350 MWh) of blue hydrogen by 2027 and rising to 30 TWh per year (equating to 3500 MWh) of production after 2030. Stakeholder engagement with the developer identified that water has been sourced for the initial hydrogen development phase from within an existing consent and that work to fulfil water requirements beyond 2030 is ongoing and considering a range of options including effluent reuse, groundwater abstraction and rainwater harvesting. Abstraction of groundwater will risk saline intrusion and deterioration of groundwater quality.

Figure 10: Photograph showing EET Fuels Stanlow refinery and HyNet area south of the Mersey estuary.

Green hydrogen refers to the creation of hydrogen gas via electrolysis of water powered by renewable energy and will initially be developed at a considerably smaller scale than blue hydrogen at two new standalone plants at Ince, Cheshire. Developed by Cheshire Green Hydrogen, about 12 tonnes of hydrogen will be produced per day, and a similar sized plant at Trafford, Greater Manchester, developed by Carlton Power, with the ability to scale up. There are also thought to be at least two potential hydrogen users, Kelloggs and Pilkington Glass that are also aiming to develop hydrogen production to use on their existing industrial sites, with another plant planned in Liverpool. See Annex 6 for further information.

The electrolysers are reported to be relatively compact, transportable by road in a container and are designed to stand alone or link together for larger demands at individual sites. Water treatment is also built into the container. Stakeholder engagement identified that these developments are initially planned at a relatively small scale, and the sourcing of water subject to delivery infrastructure being put in place was not considered to be a problem.

There are also proposals for a new hydrogen production project at Ineos, Runcorn, referred to as Quill 2. Hydrogen production already takes place at this site, and has a capacity of up to 200 MW, from a chlor-alkali process (Annex 6). This uses a membrane between electrodes permeable to sodium (Na) but not chlorine (Cl) allowing simultaneous Cl_2, H_2, and NaOH production. The plant currently operates at reduced capacity producing 10,000 tonnes of hydrogen a year, most of which is burned in boilers.

Stakeholder engagement reported that business models and finance regimes in the UK make hydrogen production challenging. They also believe that their current abstraction licences offer enough capacity for their future needs up to 2050. However, analysis will need to be undertaken to understand the future viability of these licences in the face of a changing climate and water availability. Ineos felt that flooding and high flows were more likely to be an issue than low flows for the north-west region and have already risk assessed flooding infrastructure and damaged equipment.

Hydrogen storage to balance the supply system is planned to take place in solution mined salt caverns near Middlewich, Cheshire. Some of this development is currently in place and permitted for storage of natural gas. During stakeholder engagement, Ineos indicated that currently brine demand is low, and if demand for gas storage increases, they have the option to create storage by purging brine and discharge to the Mersey estuary to develop gas storage quickly. The risk of environmental impact will require careful management, under current market conditions creation of salt caverns for hydrogen storage is not considered financially viable by them.

Carbon capture and storage projects are planned at six existing industry locations and include the power, waste incineration and cement sectors. Five of these plants are located on the English side of the border. The design of the post combustion carbon capture storage plant aims to achieve capture rates of 95% for carbon dioxide.

They will use solvents, including amines, in an absorber column to capture CO_2 from the flue gas that has been cooled. The solvent with the captured CO_2 is heated in a stripper column to separate the CO_2 from the solvent and the solvent is reclaimed before return to the absorber column where it is used again. The Tata site at Winnington, Cheshire, is currently operating and collecting 40,000 tonnes of CO_2 per year from a combined heat and power plant. The CO_2 is then used in a manufacturing process. Cooling at this plant uses a closed-circuit system that utilises a glycol coolant. This passes through heat exchangers that use abstracted water from the River Weaver to remove the heat and is then returned to the river to dissipate the heat load.

Figure 11: Tata Chemicals Europe CHP and connected CCU plant with associated carbon dioxide absorber in foreground.

The Encyclis plant at Ince, Ellesmere Port, is aiming for operation in 2027. It is proposing a different gas cooling system where hot flue gas coming from the waste energy recovery facility (ERF) is cooled from 140°C to 40°C to pass through the absorber columns. The condensate generated from the flue gas from the ERF is either collected into the carbon capture facility or can be used in the facility's coolers which require water.

The Evero carbon capture process on a waste wood ERF, also at Ince, is expecting use of Mitsubishi Heavy Industries capture technology to collect 250,000 tonnes of CO_2 per year. The company indicated during stakeholder engagement that they were currently in discussion with other parties about network capacity and water demand required for cooling purposes.

Viridor at Runcorn have applied for a new permit for carbon capture to capture 900,000 tonnes of CO_2 per year from their energy recovery plant which is permitted to accept 1.1million tonnes of waste per year. Although the application is made based on monoethanolamine (MEA) their intention is to vary the permit to use a proprietary solvent prior to commissioning. They aim to use hybrid coolers to make use of the generated direct cool condensate because the water supply required for direct cooling is much more than the water available in the water company network operated by United Utilities' (UU).

Water demand was calculated on plans for known HyNet assets using the expected scale and technology for each process, information from the literature review (see Annex 4) and stakeholder engagement (see Annex 6). This has been summarised in Table 2. It should be recognised that this will be an underestimate as it reflects projects that are in the public domain only. Stakeholder engagement suggested additional water users, though these details could not yet be shared. The water intensity of the EET Fuels blue hydrogen production process has been indicated as 17.4litres of consumptive water demand to produce 1kg of hydrogen (Mbaguta, 2021), including treatment, process and cooling requirements). This water intensity results in a projected 4.3Ml/day consumptive demand in 2030. At stakeholder engagement it was stated that water for HPP1 plant would be sourced from an existing United Utilities abstraction point from the River Dee. This demand would rise to 43Ml/day consumptive demand for future phases by 2050, that will need to consider other water sources.

Green hydrogen production has been characterised at the Carlton Energy Trafford Park site with a consumptive water demand of 35.4litres per kilogram of hydrogen produced and equating to 0.4Ml/day demand in 2030 rising to 5Ml/day should the plant be scaled up to prediction.

By comparison with blue hydrogen, the current demand and scale of known green hydrogen projects produce a relatively modest demand, less than 25% of known blue hydrogen projects, scaling up to 9.7Ml/day in 2050, however, it is anticipated that this is an underestimation based upon the industry's suggested expansion of this sector. Water demand for conversion of existing industry boilers to hydrogen has not been considered in this project as it only replaces fuel in an existing process.

The type of cooling technology employed in a CCS process is a significant factor determining water demand. Air-cooling systems do not use cooling water and instead use air condenser tubes, producing direct cooling by using conductive heat transfer from ambient air blown by electric fans. These systems greatly reduce water demand to $0.01m^3/tCO_2$. Open-loop, or once-through, systems rely on a high volume of raw water abstraction that is discharged back to the source following heat exchange and so have a relatively low consumptive water demand of $0.2m^3/tCO_2$.

Recirculatory, closed loop, or evaporative cooling systems recirculate cooling water and lower temperatures are produced because of the evaporation of this water. Periodic discharges of blowdown water are required to purge evaporative build-up. These systems have the highest water consumption intensities of the three, at $2.6m^3/tCO_2$ but require less abstraction from, and return of water to a source, than open-loop cooling.

The CCS plants that have confirmed their cooling method are a mix of systems. Whilst it is important to consider both gross and consumptive water use, we have focussed on consumptive use as this directly impacts upon water availability. Estimates of water use are shown in Table 2.

We have been informed that additional water requirement at the Encyclis plant will be close to zero as water will be generated in the ERF process. The Viridor plant is also considering a system that would reuse condensate, like Encyclis, however, additional water would also be required particularly in periods of higher temperatures during the summer months. It would look for this additional supply from an existing holder of a River Dee abstraction. Overall consumptive demand for a closed-loop system of this nature would equate to 6.5Ml/day. For assessment purposes it was assumed that this plant would not be operational before 2030. Also, developers will need to take into consideration that existing permanent licences could be subject to change after 2028. Powers from the Environment Act 2021 will allow the EA to vary or revoke licences without being liable to pay compensation if the abstraction is unsustainable or causing environmental damage.

Stakeholder engagement identified that the EET Fuels CCS plant is being designed based on no additional water requirement, to do this air cooling will be utilised as much as possible where it does not adversely affect energy efficiency or capture rate.

Evero have shared their process water requirements for CCS as 71.98m^3/hr (1.72Ml/day). They intend to meet 0.5Ml/day of this demand with recovered water from the EfW plant operation, leaving a required additional demand of 1.22Ml/day. Evero anticipate that this demand will be met from a potable water supply. Developers will need to continue to engage with water companies and the regional water resource group to ensure security of supply.

The Winnington CCU abstracts approximately 900m3/hr (21.6Ml/day) of water from the River Weaver to serve an open-loop cooling system with indirect contact, this is a non-consumptive use and is returned to the river to dissipate a heat load.

Asset	Asset Type	Assumed Source	2030		2050	
			Scale	Demand (Ml/d)	Scale	Demand (Ml/d)
Essar/Vertex, Stanlow	Blue Hydrogen	Surface Water	350 MW	4.3	3500 MW	42.7
Cheshire Green, Protos	Green Hydrogen	Potable Water	*(Assumed not operational)*		18 MW	0.5
Carlton Power, Trafford	Green Hydrogen	Potable Water	15 MW	0.4	200 MW	5.1
Inovyn CV, Quill II, Runcorn	Green Hydrogen	Surface Water	*(38 MW)*	*(1)*	200 MW*	4.1
Connah's Quay CCS	CCS	Surface Water	1200 kt CO_2/yr	8.7	2400 kt CO_2/yr	17.3
Protos Encyclis ERF CCS	CCS	Potable Water	500 kt CO_2/yr	0	500 kt CO_2/yr	0
Viridor, Runcorn ERF CCS	CCS	Surface Water	*(Assumed not operational)*		900 kt CO_2/yr	6.5
Evero EfW/MHI BECCS	CCS	Potable Water	250 kt CO_2/yr	1.2	250 kt CO_2/yr	1.2

Winnington CHP with CCU	CCS	Surface WATER	*(2 kt CO_2/yr)*	*(0.3)*	*(2 kt CO_2/yr)*	*(0.3)*
Ince Low Carbon Power Project	Generation	Surface Water	*(Assumed not operational)*		1750 MWe	20
*162MW additional demand, 38MW operational currently.						

Table 2 Summary of assessment of water demand for known HyNet assets.

All sites that plan to discharge wastewater must apply for an appropriate permit unless the discharge is clean rainfall runoff. To discharge anything other than non-domestic sewage into the public foul sewer, a consent for trade effluent, or a trade effluent agreement, must be obtained from the relevant sewerage undertaker and may require authorisation under EPR.

Limited details are known about the expected wastewater volume and quality from most future HyNet sites, therefore based upon current information it is difficult to assess whether the water environment has capacity for wastewater arisings from HyNet. Most HyNet sites are likely to require bespoke discharge permits as they are discharging close to designated or protected ecological sites. This has the potential to cause delays to the implementation of developments.

It is likely that further studies will need to be undertaken to determine and collate a more quantitative data set on future HyNet discharge quantity and quality, so that risks associated with permit applications can be minimised. This could also allow for an integrated catchment modelling study to be undertaken, providing a better estimation of the combined impact of HyNet, in combination with other existing discharges on receiving water quality.

Most of the surface water within the HyNet area currently has WFD ecological classification of ‘moderate’ or ‘poor’. The reasons vary and there is no clear, over-arching reason for the current state. Analysis suggests that a combination of industry sectors and legacy pollution issues are often responsible for the underlying water quality issues, making it difficult to highlight a specific area of concern for future HyNet assets.

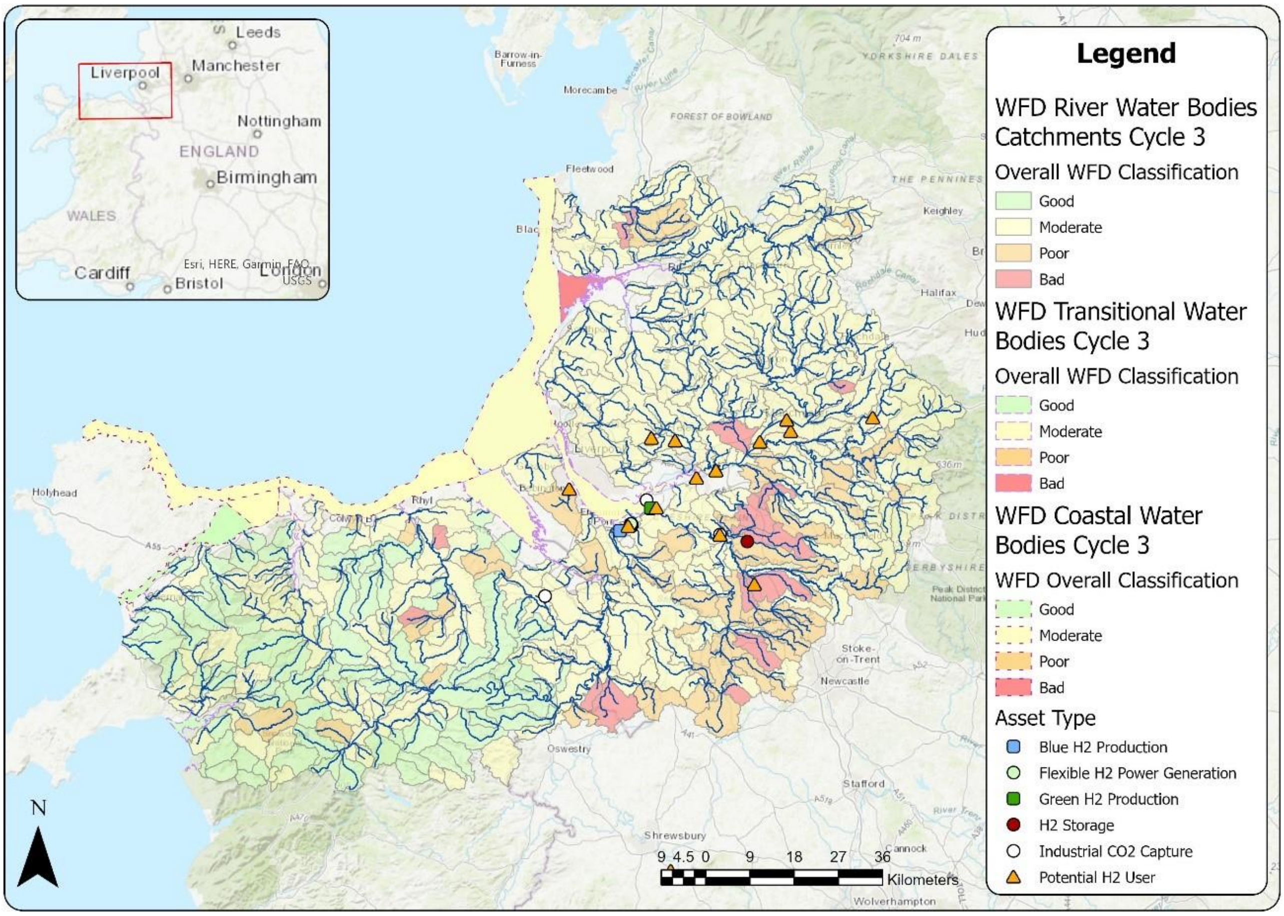

Figure 12: The overall WFD (cycle 3) classifications for river water body catchments, transitional water bodies and coastal water bodies, within the HyNet project area.

Most stakeholders involved in developing sites within HyNet indicated that they had considered wastewater arisings and planned to discharge effluent either into a nearby sewer network or water course. Some indicated that they also planned to treat effluent which may also produce a solid waste for disposal.

Potential environmental impacts from discharges will include the high salinity of brine from new salt cavern solution mining for hydrogen storage near Middlewich. Also, from carbon capture plants, condensate from compression / dewatering activities, cooling system blowdown and for those using amine solvents a final stage of acid wash to minimise emissions of amines and breakdown products to air, an acid scrubbing liquor which will need treatment before discharge (on or off-site). This provides potential for nutrient (N), ammonia and new pollutants in receiving waters which might also be subject of lower dilution in potentially reduced river flows with possible significant impact for the smaller water bodies. The stakeholder engagement indicated that industry did have a focus on water reuse, limiting the volume of expected HyNet discharges. Many suggested that future wastewater discharges will have minimal environmental impact, but little quantitative data was available to support this. Notably, future impacts of climate change and other pressures on receiving waters do not yet appear to have been considered.

There was a lack of centralised data on volumes, compositional information and exact location of wastewater currently being discharged. Collation of current discharge details would enable comparisons to be made with future estimations of water usage and corresponding discharge rates. In doing so, more extensive integrated catchment modelling could be undertaken to better understand the combined risk that HyNet poses to the water environment.

To date, the largest HyNet project is the EET Fuels blue hydrogen development, Stanlow, Ellesmere Port. The plant has consents for water discharge to both sewer and surface water and are proposing to use both, aiming to stay within existing consent limits. The current plant discharges wastewater into the Manchester Ship Canal with a discharge flow limit of 90,000 m^3/day. Consequently, an increase in process discharge volume to 413.2 m^3/day by 2030, or 4,132 m^3/day by 2050, would still only account for a negligible part of the current discharge permit limit (approximately 0.5% or 5% respectively). Therefore, it seems unlikely that this relatively minor additional discharge volume will cause a breach of permit conditions or worsening of receiving water quality.

EET anticipate that there will be no new pollutants in additional to those produced by the existing refinery as the plant currently handles amines. It therefore seems unlikely that future plant waste effluent will exceed current permit limitations for the Stanlow site. As a result, the water quality impact is likely to remain at acceptable levels in the future, unless the background water quality of the Manchester Ship Canal changes significantly, causing environmental standards to become more stringent.

There are no solid waste emissions planned except for the solids removed from treatment of condensate from the carbon capture plant which contains catalyst. This waste stream will be recycled in cement manufacture. Where raw water is treated to remove solids, the solids are currently sold on to the agricultural sector as a fertiliser and plans are to continue doing so for water treated for blue hydrogen production. There is the potential for diffuse pollution as a result of run off when solid waste is used as a fertiliser.

Most green hydrogen will initially be generated using containerised technology. The water fed into the process is of drinking water quality and through the process minerals are removed. The waste product is a concentrated stream which the developer stated during stakeholder engagement to be readily dischargeable to surface water at the Cheshire Green hydrogen site following water quality assessment. The Ince Protos Park does not currently have a foul sewer network near to the site, so wastewater may need to be discharged into the local surface water drainage network which feeds into the Mersey estuary or a network with sufficient capacity built.

Solution mining is undertaken by Ineos and Inovyn near Middlewich to create salt caverns currently used for storage of natural gas and in future, subject to necessary consent, hydrogen. Presently the calcium or magnesium carbonate impurity removed while purifying the brine is returned down these boreholes under an Environment Agency permit. Potential environmental impacts will include high salinity brine from the creation of salt cavern storage. This potential would be increased if there is no market outlet for the brine.

Brine is transported to Runcorn by pipeline and currently used for salt and chlorine production with a purge to the River Mersey. The existing membrane electrolysis process produces a weak waste brine that is discharged into the Western Canal and ultimately flows into the Mersey. These discharges are currently consented.

Unlike the Cheshire green hydrogen project, the Kellogg's site and Pilkington Glass site are located at existing manufacturing facilities with well-established drainage networks or wastewater treatment processes therefore the developer considers that wastewater could be discharged to sewer rather than directly into the local environment.

At this stage six carbon capture plants are being planned in HyNet, including three as part of EFW facilities, one at the blue hydrogen production plant and a further one that is currently operating at a CHP plant.

There is currently limited foul drainage at Ince Protos Park, developers have incorporated treatment into plant design to reduce and reuse water. The developer of the Encyclis CCS plant considered that water from the various water treatment processes on site, including acid wash, blowdown and reverse osmosis plant, could be reused within the overall process. This could be achieved by integrating the ERF facility with the CCS plant.

The Evero BECCS CCS proposal, also at Ince, whilst looking to maximise water reuse is planning a small process water effluent discharge to surface water (Manchester Ship Canal) that cannot be further recycled through a planned water recycling treatment plant. EET Fuels, Stanlow, will also make use of condensate effluent from the CCS plant which after cleaning of sulphur dioxides and nitrogen oxides, can be reused.

At the Viridor, Runcorn CCS development it is understood that the cooling towers would have a purge through a water treatment facility which enables multiple cycles within the hybrid coolers, a similar system to that in operation at the ERF. Effluent from the hybrid cooling towers will eventually discharge into the Manchester Ship Canal. The waste from the acid wash from the absorber tower generates reclaimed water and hazardous amine sludge waste that will be disposed off-site.

The Winnington CCU plant operates a water-cooling system that is non-consumptive with water returned to the river to dissipate the heat load, however, this has potential to be affected by climate change through reduced river flow and higher river temperatures that could impact efficiency.

For the majority of known HyNet sites, it was not possible to estimate the quality of future wastewater effluent streams due to a lack of data from the literature review and relevant stakeholders. Consequently, a comparison of current permit restrictions and future water discharge data was not possible. Instead, stakeholder assumptions on future wastewater effluent quality and an estimation of future discharge volumes are detailed in Table 3. Future discharge volumes have been estimated for green hydrogen production using values of 0.7litres of reject water discharged per litre consumed, whilst CCS assets discharge volume has been estimated using stakeholder insight where possible. The receiving waterbody is also included in Table 3, so that the factors currently impacting water quality can be considered.

HyNet Site	**Stakeholder Comments on Future Wastewater Discharge**	**Estimated Future Discharge Volume (m^3/day)**	**Receiving Waterbody**
Runcorn Viridor ERF CCS	Purge effluent from hybrid cooling towers would still be of sufficient quality to discharge into the Manchester Ship Canal.	Volume uncertain as to fluid to be recycled through multiple closed-loop cycles	Manchester Ship Canal
Ineos, Potential H Storage	Potential for wastewater effluent to be very saline, so discharge or disposal must be carefully considered.	Unknown	Unknown
Cheshire Green H, Protos	Wastewater will be discharged into Protos Sustainable urban Drainage Systems (SuDs) network, until treated to an appropriate standard and discharged into the river.	Estimated 310 m^3/day for 18 MW by 2050 (Mbaguta, 2021).	Unknown
Evero EfW and MHI, BECCS	The process water effluent, discharged at 5 m^3/h, that cannot be further recycled in Evero's water recycling treatment plant, would potentially be discharged into the Manchester Ship Canal. The	121 m^3/day by 2030 (stakeholder disclosed)	Manchester Ship Canal

	water quality is thought to be suitable for discharge into a watercourse; at no point do amines meet the process water. Evero intends to advise on temperature or flow impacts. The other option considered is disposing the effluent into a local drain at Protos Park.		
Ince Low Carbon Power Project	n/a	Estimated 10,700 m^3/day from discharge limit of similar sized plant.	Manchester Ship Canal
Winnington CHP with CCU, Northwich	Switching to hydrogen fuel would not produce a waste stream. The acid wash wastewater generated would be disposed into United Utilities' sewer network.	914 m^3/day return flow of cooling water.	River Weaver
Inovyn CV, Project Quill 2, Green H	Weak waste brine undergoes pH adjustment at a treatment plant then discharged into western canal, ultimately flowing to the Mersey.	Estimated 650 m^3/day at 38 MW (Current and 2030). 3400 m^3/day at 200 MW (2050). (Mbaguta, 2021)	Mersey estuary
Trafford Green H, Carlton Power	Small quantities of wastewater discharged from the electrolysis process is suitable to be released into the sewage system in Trafford.	250 m^3/day at 15 MW (2030) and 3400 m^3/day at 200 MW (2050) (Mbaguta, 2021)	n/a
Protos Encyclis ERF CCS	There is no foul wastewater discharge from the carbon capture facility. Only clean surface water is discharged into the drains near the Ince Protos Park. Acid wash is used to control the amines in the emissions from the carbon capture stack. The blowdown from the coolers and	n/a	n/a

	the acid wash on site is treated and the polished water is reused in the carbon capture process. Currently Encyclis is looking at options for reverse osmosis (RO) with Electrodeionisation (EDI), in which case the return would be sent to ERF.		
Keuper Gas Storage, Byley	There is an agreement with the Environment Agency regarding the amount of brine allowed to be discharged into Western canal and Mersey and is currently maintained under the limit.	n/a	Mersey estuary

Table 3. Stakeholder comments on future wastewater discharge quality, including estimated discharge volumes and associated receiving water course.

Climate change is one of several drivers impacting water availability in the north-west, accounting for 14% of the total drivers of water need by 2050. It will likely lead to greater impacts and variability in seasonal weather patterns and rainfall. Although it will have an impact, mainly in changes to seasonal weather patterns, other aspects such as environmental water requirements (sustainability reductions), water requirements of the energy sector, growth in industry and population growth, are pressures that will increase due to a lack of water availability. The trend towards more precipitation falling with more intensity is likely to cause an increase in overland flow resulting in more variability in river levels, particularly in fast reacting catchments to rainfall, and could theoretically result in less infiltration and aquifer recharge. Winter river flows have increased in some upland western catchments with an increase in frequency, duration, and size of flood events. The overall result could be surface water sources may be less available for periods throughout the year as river levels spend more time at low flows, due to more frequent prolonged dry weather periods, before less frequent rainfall events. Evidence of change to evapotranspiration is limited, however, it is likely to increase towards 2080 and needs consideration when assessing future water availability.

Sea level rise is predicted at all locations around the UK and will rise by between 0.4m and 1m by 2100. HyNet is not coastal but due to its proximity to the Irish Sea it may be affected by rising sea levels. While sea levels do not affect water availability from surface and groundwaters directly it may push the tidal limit further upstream, and quality of both surface water and groundwater will be directly impacted from saline intrusion and could be particularly relevant for the length of the Mersey estuary up to Warrington.

Public water supply companies have calculated the yearly impact of climate change upon the Water Resource Zone (WRZ) as part of their Water Resources

Management Plan (WRMP) process. However, this does not account for seasonal variations in water availability. Evidence identified through the literature review (Annex 4) indicates that the greatest impact of climate change in the north-west will be variability in seasonal weather patterns including more frequent prolonged dry weather periods, ultimately impacting water availability.

The literature review (Annex 4) indicates that projected groundwater recharge may be somewhere in the range from a 30% reduction to a 20% increase. Similarly, seasonal predictions indicate that in the near future (2020-2049) there will generally be less groundwater recharge across the UK, particularly in summer, with limited change in winter. Seasonal recharge becomes more divided in the far future (2050-2079), with significantly less recharge in summer (50%) and more recharge in winter (~20%). There is currently no quantitative evidence by which to state that future groundwater availability at HyNet north-west would deviate from current levels.

Stakeholders that identified the public water supply as their water source will be supplied by United Utilities (UU) who are proposing conditional agreements to the HyNet companies for the volume currently requested. However, alternative sources will need to be used if further water is required. UU is not agreeing to provide a supply above that which is currently requested in the future. They stated that the volume of water that HyNet would require is greater than the estimated surplus of the Strategic WRZ, where many HyNet assets are located. (draft WRMP documents (Annex 5, Table 4.5)

United Utilities revised draft WRMP24 indicates an 11.1Ml/day surplus water in the Strategic WRZ during 2030-31, delivered through demand management options. (Annex 5, section 4.2.2)

The power sector is estimated by WRW to require 2.4 Ml/d by 2029-30 across the WRW region (Water Resources West, 2022b). Due to the modelling method used to calculate these estimates WRW does not provide a WRZ or more local breakdowns of power water requirements. However, the sector breakdown indicated that this navigation requirement most likely is not within the HyNet area but would be in upstream areas (Annex 5, Section 3.2.1). Removing navigation requirements from WRW's estimation of non-public water supply demand for UU's Strategic WRZ leaves a requirement of 103.35 Ml/d, an increase of 2.53 Ml/d from the recent actual daily water abstracted. This additional volume is available in the existing licences (Water Resources West, 2022b). Therefore, it is assumed that if there are no reductions in licensed max annual abstraction volumes, non-public water supply requirements will not be a significant limitation for HyNet.

Water trading is already occurring in the HyNet area and can be a useful way to use existing licences which are not being fully used. However, these licences are likely to be impacted by sustainability reductions and may result in water trading being less feasible.

With the current assumptions and known water requirement for HyNet there could be sufficient water available in 2030. However, there are large uncertainties around the water requirements and sustainability reductions which may alter this assessment. Reducing this uncertainty would improve water resource planning.

At 2050, and based on a bottom-up estimation, even if licensed maximum annual abstraction volumes are not reduced it is likely there will not be sufficient water available to support HyNet based on the information currently in the public domain (the bottom-up estimation). However, an overall high-level view assumes that any required sustainability reductions will be known prior to 2050 and plans will include these reductions and any required alternative water sources will have been developed or be in development. Therefore, there could be sufficient water for HyNet in 2050, providing it is considered early and fully in water resource planning.

The literature review (Annex 4) explored climate change literature for the HyNet area. Figure 13, below, (taken from Annex 5) shows that there is an expected surplus between 1Ml/day and 50Ml/day in the four WRZs near the HyNet region. However, it also shows a deficit of between 100Ml/day and 249Ml/day in Severn Trent's Strategic Grid WRZ, which is within the WRW region. This may have an impact on the water available in the HyNet industrial cluster due to the potential for large in-region transfers. Transfers already exist within the WRW region and by 2050 may have increased in size, having an impact on the HyNet area. By comparison, Thames Water's London WRZ shows a deficit of between 100Ml/day and 249Ml/day. This may impact water availability for HyNet due to the potential Severn Thames Transfer and Northwest Transfer options, which are not currently selected as part of the preferred plans (Water Resources West, 2022), but may be by 2050.

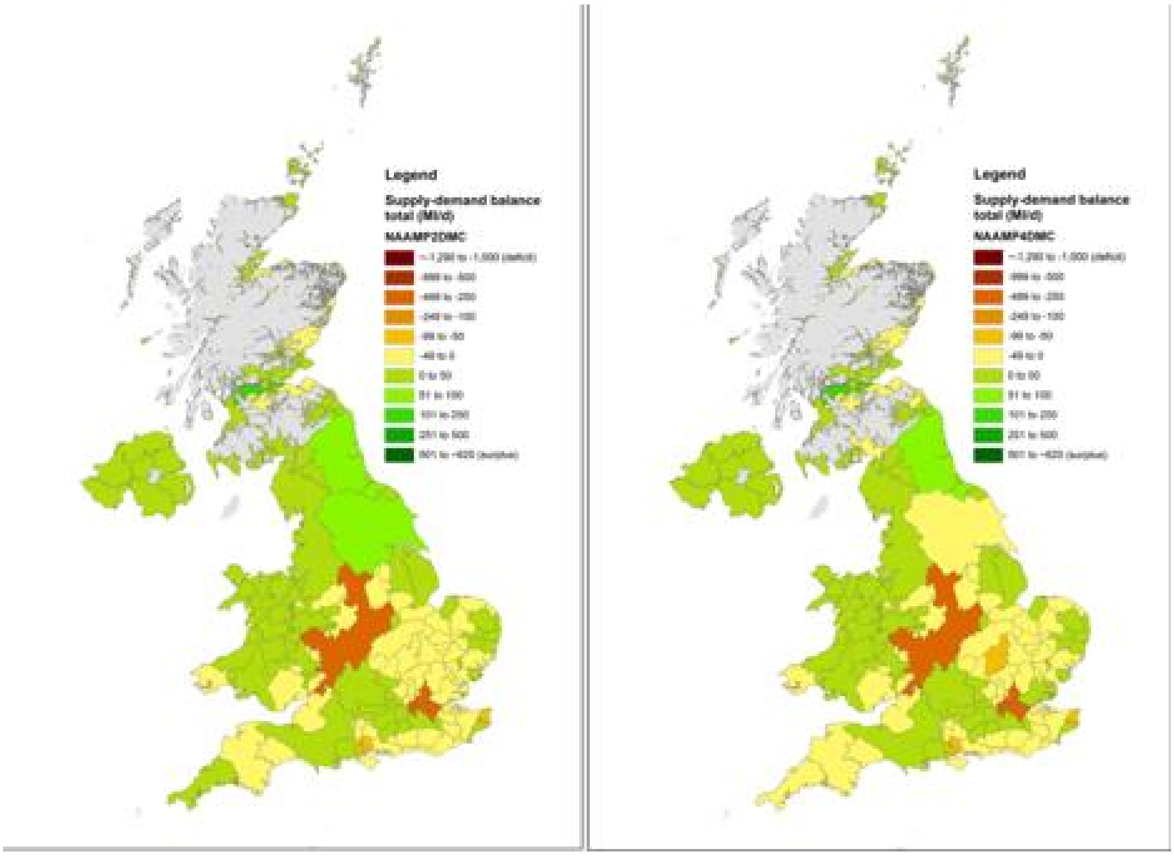

Figure 13: Supply-demand balance in the mid-century, in a 2°C world (left) and 4°C world (right), central population projection and assuming no additional adaptation action (HR Wallingford, 2020).

From the HyNet literature review (Annex 4) it was identified that the expectations for precipitation in the north-west are for similar overall precipitation, but increased seasonality, with more rainfall in the winter and less in the summer. Water requirements for HyNet assets may vary throughout the day and seasonally depending upon trends in energy use. In the UK, typically more energy is used in the winter, which is when there is a greater volume of water available in the HyNet industrial cluster. An increased understanding of the seasonality of water requirements of HyNet assets may present some water availability opportunities such as variable abstraction licences.

It is understood that United Utilities have conditionally agreed to provide water to some HyNet assets, providing the amount agreed now, but will not be obliged to provide more in the future. The revised draft WRMP24 indicates 129.7Ml/day surplus water in the Strategic WRZ during 2049-50, delivered primarily through demand management options, which are not always reliable for their water saving benefits.

Sustainability reductions are being considered as the required abstraction licence reduction for a catchment to reach its 'Environmental Destination' and it is assumed that by 2050 the scale of impact of sustainability reductions will be better understood and uncertainties around planning removed. Therefore, it is assumed that suitable alternative water sources have been or will be developed and sustainability reductions will no longer be a risk to water availability for HyNet. This will be dependent on large schemes being identified, designed, built and commissioned within the next 25 years.

Water companies should not have the sole responsibility for planning the future water need. Industry will need to actively engage in future water resource planning to ensure long term security of supply, alongside developing their own sources, potentially in collaboration with other water users.

The power sector is estimated by WRW to require 131.90Ml/day for 2049-50 across the WRW region (Water Resources West, 2022b). Due to the modelling method used to calculate these estimates WRW does not provide a WRZ or more local breakdown of power water requirements. Navigation requirements are estimated to remain the same in the Strategic WRZ, at 154.63Ml/day for 2049-50 and an increase in water requirement for the chemical sector with a moderate area presence at +9.96Ml/day. The impact this will have upon water availability for HyNet is dependent upon the impact of other pressures such as sustainability reductions and climate change.

The potential for water trading may decrease by 2050 with reduction in maximum annual abstraction volumes, as the licences would be using a greater proportion of the reduced licence.

5. Stakeholder engagement and review of stakeholder responses

5.1 Overview

This section covers the findings from discussions with various internal and external project stakeholders regarding air quality impacts from the developments within the Teesside industrial cluster, and water quality and water availability impacts from the developments within the HyNet industrial cluster.

5.2. Were the engagement objectives met?

Following the lessons learned from Phases 1 and 2, an extensive targeted engagement programme, over 3 months, was carried out. This involved online meetings with an Environment Agency (EA) presentation followed by questions and answers. These meetings were well received, leading to participative conversations. Workshops with trade associations helped the EA reach out to more organisations. There were some concerns about commercial confidentiality beforehand and during some of the meetings, careful chairing of workshops addressed this risk, however, useful knowledge sharing still took place.

We engaged with stakeholders to raise awareness of air quality, water quality and water availability to identify and understand anticipated needs and environmental capacity for deployment of low carbon technologies in Teesside and HyNet industrial clusters.

Why did we engage?

To ensure key people we are working with understood what we wanted to achieve and how we would achieve it, and to communicate how decisions will be made. To do this, we needed to work with interested groups within the Teesside and HyNet industrial clusters, so they could help shape future work and we can build good working relationships. We wanted to:

- raise awareness of environmental capacity in the industrial clusters
- identify and understand needs and capacity by sharing expertise and understand what technology industry intend to use
- identify benefits for all involved

Internal objectives

Our objectives within the EA were to ensure our internal colleagues:

- understood the project and implications for environmental parameters that we manage and regulate

- helped us with our investigation into the technical content of air quality, water quality and water availability
- shared learning and standardised approaches to identifying environmental capacity and engagement in different clusters

External objectives

Industry

From our engagement with industry stakeholders, we wanted to:

- understand the challenges that industry has encountered during the planning of projects
- show industry that we are an enabler in the transition to net zero,
- strengthen the relationship with industry by conducting two-way conversations
- make industry aware of environmental capacity issues that they will need to consider and adapt
- understand industry water needs to enable the development of low carbon technology

Local Authorities

From our engagement with local authorities, we wanted to:

- encourage information exchange and be informed of forward plans or details on specific developments that will impact the capacity of the environment to absorb industrial pollutants and challenge water resources
- ensure understanding of the types and significance of environmental capacity issues, including what environmental resources developments require their impact in a specific location
- encourage them to raise awareness of environmental capacity issues at an early stage
- raise awareness about the EA's role in regulation and enabling net zero

UK regulators

From our engagement with UK regulators, we wanted to:

- encourage ongoing dialogue about generic plans, challenges and approaches
- ensure that we shared the same approach to the challenge as Natural Resources Wales, Northern Ireland Environment Agency and Scottish Environment Protection Agency
- work with Natural England to improve our strategic understanding and support statutory bodies in regulating emissions of nutrients to air and water from the Teesside and HyNet industrial clusters

- discuss air quality issues on Teesside with the UK Health Security Agency to understand current health impacts attributed to air quality and advice on health impacts of novel emissions from low carbon technologies

Water companies and water resource groups

From our engagement with water companies and water resource groups we wanted to:

- gain more information on strategic water resource and supply plans for low carbon technology deployments and the impact that will these have on future developments
- improve our understanding of wastewater network capacity to cope with a possible increase in wastewater generated

5.3. What impact did it have?

All the stakeholders we engaged with were supportive of these early discussions on air quality in the Teesside industrial cluster and water quality and availability in the HyNet industrial cluster. Addressing these issues promptly could help mitigate potential delays and ensure compliance with legislation and regulatory standards. This will help provide investors with confidence in the long-term sustainability of low carbon technologies in the Teesside and HyNet industrial clusters.

Several themes emerged regarding air quality within Teesside:

Emissions and monitoring

- the introduction of low carbon technologies has the potential to alter current emissions within the Teesside industrial cluster
- burning hydrogen is anticipated to increase NO_x, ammonia and $PM_{2.5}$ emissions and nitrogen deposition
- hydrogen production with carbon capture or applying carbon capture to existing or new industrial processes will introduce new pollutants such as amines which are currently not monitored in ambient air and for which emissions monitoring standards do not exist
- background air quality monitoring for ammonia, amines and other novel pollutants associated with new industrial processes attracted to the area is required, the government department responsible for the monitoring also needs to be agreed

Habitats

- ongoing work to increase the number and total area of protected habitats is increasing, the pressure is on existing and new industry to comply with nitrogen deposition and nutrient neutrality limits
- an option to offset ammonia emissions by reducing emissions in another area, such as agriculture, is of interest to both industry and Natural England,

this would need to be assessed in greater detail to ensure that any offset reduced nitrogen deposition at the ecological sites impacted by emissions to air

Permitting

- operators have been submitting permit applications to use MEA as their solvent even though they intend to use a proprietary solvent at some stage in the future
- a variation to the environmental permit would be required to consider this change
- this could result in a substantial amount of permitting work and further delays to the capture plant operations
- permits to emit air pollutants are based on a first come, first served basis,
- the cumulative impacts of ten new industrial processes, may pose a challenge to enabling new deployments
- a revised approach to assessing cumulative impacts may be required, especially for novel pollutants for which there are currently no Environmental Assessment Levels (EALS) or background monitoring
- in addition to an increase in environmental permit applications these regions with industrial clusters will see an increase in planning applications to facilitate low carbon deployments

Several themes emerged regarding water availability and wastewater management within the HyNet industrial cluster:

- wastewater management had not been considered in detail in the planning stages by most HyNet developers
- overlooking wastewater management could require modifications to existing permits or require new permits, potentially causing significant delays in the planning process and environmental permitting, to projects
- most developers have not yet detailed the composition and potential pollutants within their wastewater discharges
- water demands and potential sources of water have been considered in more detail by companies involved in HyNet
- most companies indicated their preferred water source,
- HyNet companies have also explored technological processes that minimise water usage
- water reuse is being considered however, desalination does not currently appear to be part of company plans
- it was suggested that focusing on known developments within HyNet would lead to underestimates of likely future water demand
- the impacts of climate change on future water availability and future discharges from HyNet were rarely mentioned by stakeholders in the workshops
- some consideration of future flood risk and extremes of weather events was evident

- stakeholders noted the uncertainties in predicting future water demands and environmental impacts of HyNet
- local authorities in the region currently do not have clear, specific policies related to HyNet in their local plans, though they do have policies supporting renewable energy / net zero technology
- it is also important to point out that many local plans with associated policies were adopted pre-HyNet
- Water Resources West and United Utilities, however, have considered HyNet in their planning where details were available at the time of assessment and suggestions were made in the workshop

Evaluation of stakeholder engagement

There was a large group of participants in the trade association workshops, drawing out the breadth and depth of comments from a wide variety of stakeholders was challenging. On reflection, it would have been useful for stakeholders to provide examples of how the environmental capacity and climate impacts may challenge their deployments.

The HyNet local authority workshop could have been planned with relationships established with individual representatives rather than anonymously through generic email accounts. Some participants in the workshops informed the Environment Agency that they didn't have the authority or the expertise to comment formally.

During the Teesside local authorities' workshop, the Environment Agency were made aware that some authorities now have specific climate change teams. These climate change teams may have made a more informed contribution to the air quality discussions than environmental health teams.

Following learning from Phases 1 and 2, individual engagement worked well with stakeholders, trade associations and individual companies and we received valuable detailed information that we would not have achieved had we only sent them a questionnaire.

A smaller set of questions for discussion at the workshops may have been better as quite often there was not enough time to receive feedback on all the questions.

The internal EA workshops were well attended, structured, and at the right pace, the content was relevant, and each participant had the opportunity to contribute. In Teesside, the workshop with Natural England was especially productive. We explored existing relationships and roles with the Environment Agency. As a result of this, improvements to this partnership are being discussed at a national and local level.

Overall, the stakeholders in Teesside and HyNet were supportive of early discussions. Addressing concerns promptly could mitigate potential delays. It also ensures compliance with regulatory standards, provides investors with confidence in the long-term sustainability of Teesside and HyNet industrial clusters, and ultimately facilitates the successful realisation of both clusters.

6. Conclusions and Recommendations

Phase 3 of this project reviewed environmental capacity for the deployment of carbon capture and hydrogen production in the Teesside and HyNet industrial clusters. Phase 3 reviewed the capacity challenges of water availability and water quality in HyNet, and air quality in Teesside.

The project continued to work with and expand on a network of local and national Environment Agency specialists, and leading industry, regulatory and spatial planning stakeholders to gather knowledge, compile and interpret evidence and seek stakeholder views on specific environmental capacity issues.

In conclusion, the Teesside industrial cluster has experienced an improvement in air quality over the last 10 years, and Air Quality Standards (AQS) are currently being met. However, a lack of baseline data will challenge the understanding of future air quality impacts from low carbon technologies. The adoption of hydrogen and industrial fuel switching could result in elevated nitrogen oxides emissions, nitrosamines and nitramines that will require comprehensive strategic air quality management strategies to address possible impacts.

In HyNet an assessment of abstraction licences in 2012 and 2023 found that surface water may be available for licensing at volumes required for HyNet up to 2030, however, future water availability for HyNet (2030+) is less certain. Uncertainty exists around wastewater impacts in HyNet from low carbon technologies and the potential thermal, toxicological and ecological impacts around catchments across the HyNet region. How wastewater is to be managed has yet to be fully determined.

A strategic whole system view of industrial cluster development is required, involving industry, government, regulators and spatial planners to address environmental challenges facing the deployment of low carbon technologies.

Action for reducing global warming must be focussed on the permanent removal of all greenhouse gases not just CO_2. It is crucial that low carbon technologies do not introduce new or more significant greenhouses gases to the atmosphere.

The recommendations of this project are to:

Teesside

1. evaluate the environmental impacts of operational hydrogen production plants and the long-term effectiveness of carbon capture technologies in the areas of review
2. review the energy penalty associated with CO_2 removal and whole lifecycle carbon emissions to calculate actual CO_2 removal
3. consider accumulated nitrogen loads at an industrial cluster scale to assist mitigation measures and inform spatial planning decisions (this evidence gap will be partially addressed through the Environment Agency's project, *Cumulative air quality impacts from net zero technologies, due to be completed, March 2025)*

4. share publicly available source data of neighbouring sites from permit applications and monitoring reports, via a central database, this would make information easier to access

HyNet

5. carry out a cumulative impact assessment of discharges to surface water to understand the unintended consequences on habitats across planned deployments in industrial clusters and enable a balanced impact assessment on rivers and estuaries
6. further consultation by industry with regional water resource groups would be beneficial for successful development. English regional water resource groups such as WRW hold a good view of water availability in the HyNet region from the current state to the future (approx. 60 years) based on available data which will be refreshed at least every 5 years, regional water resources groups provide an overall assessment and is a good source of information for use in a centralised, strategic approach
7. regional groups to provide an overall assessment to help address uncertainties around water demand and wastewater arisings
8. water industry, developers and regulators continue to work together in a strategic way to understand and mitigate the effects of the HyNet industrial cluster on the water environment
9. create a centralised, strategic view of the hydrogen production and carbon capture network with the regional water resources groups, to understand and establish a sustainable level of national and local hydrogen network with the water available
10. individual projects in the HyNet industrial cluster need to work collaboratively with the regional water resource group to ensure their water needs are reflected in regional water resources plans, this collaboration should not just focus on the demand for water but also where that water will be sourced from

General

11. perform holistic reviews of air, land and water impacts to improve strategic spatial planning decisions by clustering low carbon technologies in less sensitive areas

Further research is needed to ensure the sustainability of industrial cluster development, the contribution towards the decarbonisation of industrial regions and the development of a national hydrogen economy. This project has identified the important areas where research will make a significant contribution to net zero targets.

Research recommendations include:

1. establish a baseline to assess the impact of new pollutants on air quality
2. monitor ammonia and amines in ambient air to help understand the contribution from new low carbon technologies processes and target regulatory control

3. explore opportunities to reduce emissions from other sources in the same region to address the challenge of environmental capacity to absorb pollutants in air and water
4. assess unintended consequences for habitats across planned deployments in industrial clusters, a holistic review of water impacts to improve strategic spatial planning decisions by clustering low carbon technologies in less sensitive areas, this has the benefit of enabling a balanced impact assessment on rivers and estuaries

7. Acronyms

AD	Anaerobic Digestion
AMP	2-Amino-2-Methyl-1-Propanol
AQMAs	Air Quality Management Areas
AQS	Air Quality Standards
BECCS	Bioenergy Carbon Capture and Storage
CAMS	Catchment Abstraction Management Strategy
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
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
EAF	Electric Arc Furnace
EALS	Environmental Assessment Levels
EET	Essar Energy Transition
EFW	Energy from Waste
ELCRs	Estimated Lifetime Cancer Risks
EPR	Environmental Permitting Regulations (England and Wales) 2016
ERF	Energy Recovery Facility
EV	Electric Vehicle
HECC	Health and Environmental Impacts of Carbon Capture
HPP1	Hydrogen Production Plant 1

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
NRW	Natural Resources Wales
NVZs	Nitrate Vulnerable Zones
NVZs	Nitrate Vulnerable Zones
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
PWS	Private Water Suply
QSAR	Quantitative Structure Activity Relationship
RBMPs	River Basin Management Plans
RNAG	Reasons for Not Achieving Good Status
SACs	Special Areas of Conservation
SAF	Sustainable Aviation Fuel
SMR	Steam-methane Reforming
SO_2	Sulphur Dioxide
SPA	Special Protected Area
SSSI	Site of Special Scientific Interest
SuDS	Sustainable Drainage Systems
UKHSA	UK Health Security Agency
UU	United Utilities
VOC's	Volatile Organic Compounds
WFD	Water Framework Directive
WRMP	Water Resources Management Plan
WRW	Water Resources West
WRZ	Water Resource Zone

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