Environmental Capacity in Industrial Clusters project - Phase 3

Technical Annex 1 Tees Literature Review

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Prepared by:

Patrick Froggatt
Technical Air Quality Director
AECOM

On behalf of:

Environment Agency
Horizon House, Deanery Road,
Bristol BS1 5AH

www.gov.uk/environment-agency

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Acronyms

$2H_2$	Hydrogen
AILs	Aprotic Ionic Liquids
AILs	Autothermal Reactor
AMP	2-Amino-2-Methyl-1-Propanol
ASC	Advanced Supercritical
BECCS	Bioenergy Carbon Capture and Storage
BPEO	Best Practicable Environmental Option
C	Carbon
CCS	Carbon Capture and Storage
CCSCU	Carbon Capture Solvent Compatibility Unit
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DAC	Direct Air Capture
DEA	Diethanolamine
ELCRs	Estimated Lifetime Cancer Risks
ELVs	Emission Limit Values
FTIR	Fourier Transform Infrared Spectroscopy
GW	Gigawatt
GWP100	100-year Global Warming Potential
HECC	Health and environmental impacts of carbon capture report
HFCs	Hydrogen Fuel Cells
IARC	International Agency for Research on Cancer
IED	Industrial Emissions Directive
LCP	Large Combustion Plant
LOHC	Liquid Organic Hydrogen Carriers
MCP	Medium Combustion Plant
MCPD	Medium Combustion Plant Directive
MDEA	Methyldiethanolamine
MEA	Monoethanolamine
MG/NM^3	Milligrams Per Cubic Metre
N_2	Nitrogen
N-amines	A Broad Category of Nitrogen-Containing Amines, Including Nitrosamines and Nitramines
NDEA	N-Nitrosodiethylamine
NDMA	N-Nitrosodimethylamine
NGD	Natural Gas Decomposition
NH_3	Ammonia
NO_2	Nitrogen dioxide
NO_x	Nitric oxide (NO) and Nitrogen Dioxide (NO2)
NPIP	N-Nitrosopiperidine
PCBs	Polychlorinated Biphenyls of EAF = Electric Arc Furnace
PCC	Post-combustion carbon capture
PEM	Proton Exchange Membrane
PILs	Protic Ionic Liquids
PM_{10}	Particulate Matter With An Aerodynamic Diameter of Less Than 10 Micrometres (µm)
$PM_{2.5}$	Particulate Matter
PPBB	Premixed Bluff Body Burner
PTR-MS	Proton Transfer Reaction – Mass Spectrometry

PZ	Piperazine
QSAR	Quantitative Structure Activity Relationship
SMR	Steam Methane Reformation
SMR-52%	Steam Methane Reforming technologies with carbon capture rate of 52%
SMR-85%	Steam Methane Reforming technologies with carbon capture rate of 85%
SO_2	Sulphur Dioxide
TCM DA	Technology Centre Mongstad
VOC	Volatile Organic Compounds

1.0 Literature Review

The aim of this literature review is to assess hydrogen's potential as a sustainable fuel within the energy sector and to explore the expanding role of carbon capture technologies, with a specific focus on their environmental impacts, technological applications, and integration into existing energy systems. This includes evaluating hydrogen's application in processes such as ammonia (NH_3) cracking and fuel switching in large combustion plants, while also considering the environmental consequences and the increasing prevalence of carbon capture technology within the Tees.

This will be addressed by:

- Exploring the role of hydrogen in the energy sector to understand its scope and implications across various applications, including NH_3 cracking, fuel switching to 100% hydrogen in peaking plant engines and off-gas engines, as well as in Medium Combustion Plant (MCP) and Large Combustion Plant (LCP) boilers.
- Identifying the range of pollutants of interest and greenhouse gases, such as carbon dioxide (CO_2), and assessing their potential environmental impacts. This involves gathering habitat information, understanding current background levels, and pathway information to evaluate how these pollutants might affect air quality and the broader environment.
- Assessing the potential impacts on air quality associated with the generation, transport, and use of hydrogen as a fuel, as well as those related to carbon capture technology. This includes examining how these technologies might influence air quality, ecology, and climate change, and identifying where current knowledge gaps exist.
- Evaluating the environmental impacts of hydrogen use and carbon capture technology within the Teesside Industrial Cluster context. A particular focus will be on identifying any air quality environmental capacity challenges that could limit development in the area.

To achieve these aims, this literature review will assess current evidence on potential emissions generated by hydrogen production and use. The review will consider:

- The formation of hydrogen, particularly grey and blue hydrogen, and emissions associated with other hydrogen production forms.
- Potential hydrogen leakage rates at various production stages, including steam methane reformation (SMR) with carbon capture, Autothermal Reforming (ATR), coal & bio gasification with carbon capture, and electrolysis.
- Other emissions directly or indirectly associated with hydrogen/carbon capture and storage (CCS), including but not limited to NO_x, NO_2, PM_{10}, $PM_{2.5}$, CO, CO_2, SO_2, NH_3, and N-amines.
- Identifying gaps in the current evidence that may inform future research directions.

2.0 Methodology

This section briefly outlines the methodology used for this study. In developing the methodology for this literature review, we have adopted principles aligned with the approach detailed in the document on the Rapid Evidence Assessments (Collins et al., 2015) [1]. This approach is recognised for its efficiency in synthesizing vast amounts of evidence within constrained timeframes while ensuring the research remains comprehensive, systematic, and unbiased.

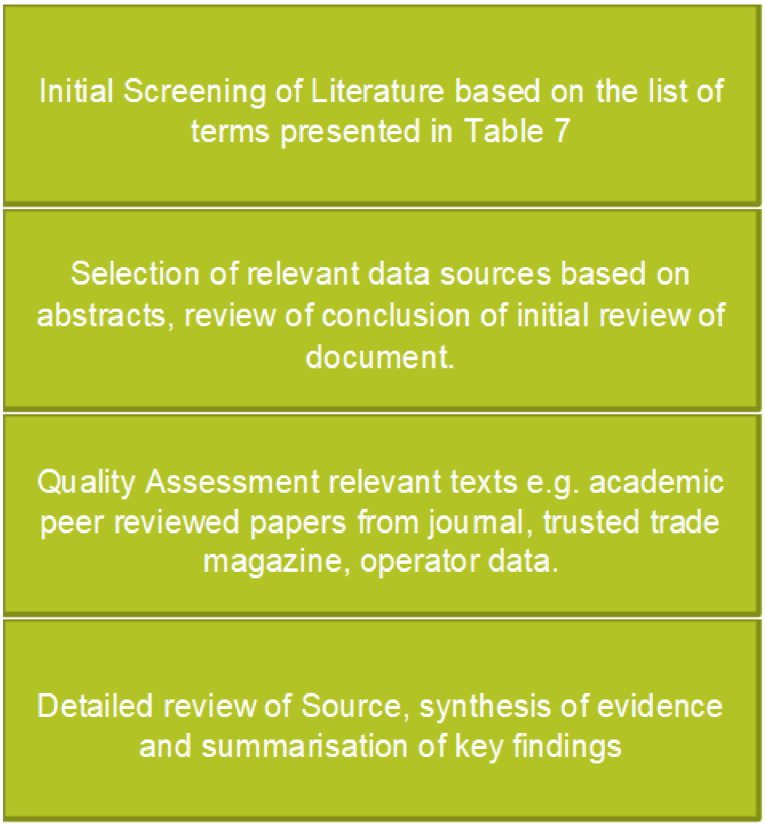
Adopting this methodological framework allows for the swift identification of relevant studies, enabling an agile response to emerging questions and the ability to update understandings in light of new evidence. It aligns with our objective to provide a clear, objective, and rigorous synthesis of existing literature on low and zero-carbon technologies, focusing on key findings and gaps in the current research landscape. This methodological stance supports our aim to contribute effectively to the knowledge in the potential effects of hydrogen as a sustainable fuel, ensuring that our review not only encapsulates the breadth of available evidence but also adheres to the highest standards of academic rigour as recommended by Collins et al. (2015) [1] in their foundational guide.

Figure 1 describes the procedure that was followed to select the most relevant available articles for the review. Irrespective of any geographical area, all relevant studies have been considered in the literature search. The process begins with an initial screening of literature based on a comprehensive list of terms relevant to the study's focus. This stage involved searching electronic databases that will be described below to retrieve publications that match the predefined search criteria. After the initial screening, there is a selection of relevant data sources, which is based on the examination of abstracts and the conclusions of the initially reviewed documents.

A two-step filtering process was applied with sources first identified for potential relevance through their abstracts, and then further assessed by their conclusions to ensure they provide substantive information for the study's objectives. The third step applied a quality assessment of relevant texts, which involves critically evaluating sources provided on website articles, academic peer-reviewed papers, articles from trusted trade magazines, and operator data. The quality of texts was assessed based on the credibility of the publication/author, the methodology of the study, the relevance to the research aims, and the robustness of the findings. Preference has been given to academic peer-reviewed papers and articles from well-known trustworthy trade magazines.

Data has been mainly collected from the most recognised operators, and information provided by governmental or reputable environmental organisations. The research design and method used are subjected to critical scrutiny to ensure sound scientific practices were followed. Here, we mainly focused on the work that was published within the last 20 years to ensure the relevance and currency of the information and data. Finally, the methodology culminates in a detailed review of sources and summarisation of key findings. This phase involves an in-depth analysis of the selected literature, extracting and synthesizing crucial data and insights relevant to the research aims.

Figure 1 - Study Methodology Outline



The source search terms, detailed in Table 1, were used to perform the initial screening of literature related to Net Zero technologies and their associated effects on air quality and ecology. This consisted of a systematic literature review of reports and scientific papers conducted through scientific databases, Google Search, Google Scholar, Scopus, Science Direct and Web of Science. Synonyms and modified versions of those keywords were also utilised. Initially, many of the keywords were used individually in the search and then they were gradually combined (i.e., using 'OR' and 'AND') in rational combinations, to find the most relevant abstracts and websites for review.

Table 1 - Review Search Terms

Search Terms for Web	Search Terms for Academic Journals
CO_2 capture technology	Carbon capture AND post-combustion AND emissions
Air pollution from Carbon Capture Technologies	Air quality OR Air pollution
Carbon Capture and Storage technology	Carbon capture AND emissions AND environmental impacts
Emissions from carbon capture facilities	Carbon capture AND emissions AND health effects
Air quality regulations for carbon capture	Amine emissions AND monitoring AND modelling
Amine emissions in power plants	Hydrogen production AND Carbon Capture systems
Environmental impacts of amine emissions	Amine emissions AND real-time monitoring
Amine-based carbon capture	Long-term effects AND amine emissions

Search Terms for Web	**Search Terms for Academic Journals**
Impacts of amine emissions on air quality	Amines AND Carbon Capture AND Nitrosamines formation
Nitrosamines and health risks	Amine emissions AND Impacts AND ecosystems OR human health
Air quality guidelines for amines	Nitramines AND Nitrosamines AND health risks
CO_2 capture process optimisation	Metal-Organic Frameworks (MOFs) AND Carbon Capture
Carbon Capture Case Studies	Carbon Capture AND Air Quality Assessments
Advanced monitoring techniques for amine emissions	Long-term effects AND amine emissions AND ecosystems OR human health
Hydrogen generation from carbon capture	Oxy-combustion AND Allam Cycle
Decarbonisation strategies	Carbon capture AND emissions AND monitoring AND challenges
Carbon capture challenges	Carbon capture AND emissions AND modelling AND challenges
Carbon capture opportunities	Hydrogen AND air quality AND impacts
Innovative amine-based capture solutions	Hydrogen emissions AND climate change
Sustainable hydrogen production	Amine scrubbing AND performance AND assessment
	Amine degradation products AND monitoring
	Allam Cycle OR NET Power Cycle

The initial search of the databases yielded 1,376 citations. The first step in refining this pool involved removing duplicates, significantly reducing the number of articles. After removing the duplicates, we conducted a preliminary screening based on titles and abstracts, which led to further exclusion of articles that did not align with the scope of our review. This process resulted in 460 articles identified as potentially relevant and available for full-text retrieval.

During the detailed review of these articles, journal abstracts or website summaries, we applied specific inclusion criteria, leading to further exclusions: 299 articles were excluded for the following reasons:

- 192 articles were excluded due to their focus being outside the scope of Carbon Capture and Hydrogen technologies;
- 10 articles were excluded because they were review articles without original research data; and
- 97 articles were excluded for not providing sufficient detail on the methodologies or outcomes relevant to our study objectives.

Ultimately, 161 articles were retained for our final review, comprising 71 articles related to Carbon Capture, 48 related to Hydrogen, and 42 focusing on both or offering other relevant insights. The following section sets out the findings of the literature review with a detailed summary of the findings, discussions and conclusions of most of the relevant papers/websites presented in Table 2 at the end of this appendix.

3.0 Low and Zero Carbon Technologies

The transition to low and zero-carbon emission technologies is an essential component of the global effort to reduce CO_2 emissions and combat climate change. These technologies encompass various forms of hydrogen production, such as green, blue, and grey hydrogen, alongside a wide spectrum of CCS technologies. CCS technologies include post-combustion carbon capture, pre-combustion and direct air capture methods, each playing a critical role in mitigating CO_2 emissions from combustion and industrial activities, though they come with their own sets of challenges and benefits.

3.1 Hydrogen

3.1.1 Hydrogen Use

The use of hydrogen is potentially a significant contributor to reducing reliance on fossil fuels and emissions of CO_2. Adding hydrogen to natural gas significantly reduces the level of CO_2, and it reduces to zero when pure hydrogen is utilised (Topolski et al., 2022) [2]. CO_2 emissions also decrease with increasing hydrogen load in the fuel mixtures, eventually dropping to zero with pure hydrogen burning.

However, fuels such as hydrogen may help reduce carbon emissions but depending on how they are converted to energy could potentially lead to worsening air quality [3]. Recent investigations into the use of hydrogen as a combustion fuel 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).

Dutka et al. (2016) [4] explored NO_x emissions in a partially premixed bluff body burner (PPBB) under various operating conditions and fuel mixtures. The study's experimental setup facilitated the examination of NO_x emissions across burner thermal loads ranging from 10 to 25 kW, with chamber wall temperatures measured between 1050°C and 1350°C. Notably, the lowest NO_x emissions were recorded at a 10 kW power load, producing 55 mg/kWh for methane (CH_4) and 102 mg/kWh for hydrogen (H_2), both at a dry basis of 3% O_2. These results were achieved with a shorter lance position, optimising the flow's momentum and turbulence, which are critical factors influencing NO_x formation.

As emission limit values evolve, it is crucial to consider these factors to accurately assess the emissions profile of hydrogen-enriched fuel mixtures (Cellek & Pinarbasi, 2018 [5]; Byworth Boiler, 2023 [6]). The study conducted by Cellek and Pinarbasi (2018) [5] focused on the performance and emission characteristics of an industrial low-swirl burner while burning natural gas, methane, and hydrogen-enriched fuels. Specifically, the study utilised a burner supplied by Termo-Heat Isı San. A.S, which was designed to operate under a constant burner load of 1,085 kW and various cooling conditions in the boiler. The experimental results revealed significant findings regarding NO_x emissions across different fuel types. For instance, at lower power loads, NO_x emissions were quantified at 55 mg/kWh for methane and 102 mg/kWh for hydrogen, indicating a substantial increase in NO_x emissions when transitioning from methane to hydrogen as the fuel source.

Douglas et al, (2022) [7] completed a study on hydrogen methane fuel blends, using correction curves for 100% hydrogen fuel the NO_x concentration is predicted to be up to 37% higher compared to traditional methane combustion. C. Douglas et al, stated that a volume-based measurement approach can indicate higher NO_x emissions for hydrogen blended systems and pure hydrogen required a correction of 36% to 40%. The study mentions that even when the mass production rate of NO_x emissions remains the same, higher hydrogen systems will report higher NO_x emissions when measured in volume-based metrics (ppmv @ 15% O_2) due to higher proportions of H_2O and O_2 in the combustion products compared to pure methane. This results from the combustion of hydrogen/methane fuel blends producing products with different compositions than those produced by pure methane combustion, leading to a discrepancy in NO_x concentration measurements.

The study by Wright and Lewis (2022) [8] undertook a comprehensive meta-analysis of NO_x emissions from the combustion of hydrogen and natural gas (H_2-NG) blends in space heating boilers. It evaluated the impact of incorporating hydrogen into the natural gas network, with a focus on blends up to 20% hydrogen by volume. This approach aligns with the UK's short-term objectives for hydrogen integration and is compatible with existing infrastructure. The findings reveal a wide variability in NO_x emissions changes, ranging from a decrease of 12% to an increase of 39% for a 5% hydrogen blend compared to pure natural gas. At the higher end, a 20% hydrogen blend could result in changes ranging from a decrease of 50% to an increase of 154% in NO_x emissions. These variations are attributed to differences in appliance types, experimental conditions, and the higher adiabatic flame temperature of hydrogen combustion.

Meziane and Bentebbiche (2019) [9] provided a numerical analysis of NO_x emissions from natural gas, hydrogen and blends of each. The key focus is on comparing the results from experimental data and two different numerical simulation schemes regarding NO_x emissions. They found that a small addition of hydrogen, just 10%, to the natural gas can result in the reduction of NO_2 and CO_2 emissions by 14% and 60%, respectively. To ensure environmental compliance during the transition to hydrogen fuel, the Environment Agency has outlined specific NO_x Emission Limit Values (ELVs) for the combustion of hydrogen within the scope of plant covered by the Medium Combustion Plant Directive (MCPD) and the Industrial Emissions Directive (IED) for Large Combustion Plant (LCP). A correction factor of 1.37 is applied to ELVs for the combustion of natural gas to obtain ELVs for the combustion of hydrogen, considering the change in flue gas volume. For instance, gas turbines greater than 50MWth will have a NO_x ELV of 68.5 mg/Nm³ when using 100% hydrogen fuel. This guidance ensures that the transition to low-carbon fuels does not compromise local air quality (EA, 2024) [10].

This inclusion of specific ELVs for hydrogen combustion reflects the regulatory framework's responsiveness to the evolving energy landscape and underscores the importance of adhering to these standards to minimise the environmental impact as the Tees Industrial Cluster progresses towards its decarbonisation goals.

Lewis (2021) [11] denoted that minimising NO_x as a by-product from hydrogen boilers and engines is possible through control of combustion conditions, but this can lead to reduced power output and performance. After-treatment and removal of NO_x is possible, but this increases the cost and complexity of appliances. Combustion applications therefore require optimisation and potentially the need for catalytic NO_x reduction units to be fitted to combustion plants that currently do not require NO_x control to achieve existing emission limits if the greatest air quality benefits from a growth in hydrogen use are to derive.

3.1.2 Hydrogen Production

Hydrogen can be generated at an industrial scale in several ways and the resultant hydrogen, while chemically the same, is named differently depending on how it is generated (National Grid, 2023) [12].

- White hydrogen: also known as "natural," "gold," or "geologic" hydrogen, is naturally occurring hydrogen found in the Earth's crust. Its discovery and potential use could play a pivotal role in addressing the climate crisis though large-scale sources of white hydrogen are yet to be identified and any subsequent extraction activities may have their own environmental impacts. Gold hydrogen tends to refer to hydrogen naturally produced by microbial activities in depleted oil wells.
- Green hydrogen: is produced through the electrolysis of water, using electricity generated from a combination of renewable energy sources, including solar, wind, and wave power (Hein et al., 2023) [13]. This process splits water into hydrogen and oxygen without relying on power from combustion, thereby generating hydrogen without any CO_2 emissions. Specifically, within the Tees Industrial Cluster, green hydrogen production is represented by the HyGreen Teesside project, aiming to become one of the UK's largest green hydrogen facilities (HyGreen Teesside), and the Protium project, which proposes green hydrogen production via Proton Exchange Membrane (PEM) electrolysis (Protium). Furthermore, EDF Renewables is developing the Tees Green Hydrogen project to supply local industry with hydrogen produced using green electricity from nearby renewable sources (EDF Renewables – Table 18).

  A subset of green hydrogen, referred to as "dark green" hydrogen, emphasises an even stricter adherence to sustainability by ensuring the electrolysis process is powered directly and exclusively by renewable energy sources, not connected to the grid which may include a mix of energy sources (Hassan et al., 2023 [14]; Yacine & Abderrahim, 2023 [15]). This ensures that hydrogen production is not indirectly associated with fossil fuel-derived electricity, enhancing its environmental credentials.

  On the other hand, when the electrolysis process is powered solely by solar energy, the produced hydrogen is sometimes specifically termed "yellow hydrogen," highlighting the singular renewable source used in its production. The classification into green, dark green, and yellow hydrogen underscores the varying levels of environmental impact and sustainability associated with the production processes, with "dark green" hydrogen representing an ideal in terms of renewable energy purity and directness (Hassan et al., 2023 [14]; Yacine & Abderrahim, 2023 [15]) This distinction ensures the production process minimises indirect associations with fossil fuel-derived electricity, reflecting the true environmental benefits of green hydrogen production.
- Pink hydrogen: is also generated through the electrolysis of water, however, the electricity comes from nuclear power generation.

- Blue hydrogen: made from natural gas via steam reforming, generates CO_2 due to fossil fuel use, however, the CO_2 is captured using carbon capture techniques, making it 'low-carbon' yet not emission-free. Within the Tees Cluster, the bp H_2Teesside project aims to become one of the UK's largest blue hydrogen production facilities, with CO_2 capture and storage capabilities (bp H_2Teesside).
- Grey hydrogen is primarily generated from natural gas via steam reforming, but it can also be produced as a by-product in various refineries and chemical processes. Furthermore, steam reforming is not limited to natural gas but can also utilise other light hydrocarbons, such as naphtha (Ingale et al., 2022 [16]; Holladay et al., 2009 [17]). The BOC Seal Sands facility, utilising natural gas through the Steam Methane Reforming (SMR) process, is a relevant example within the Tees Cluster, although it's moving towards capturing CO_2 to enhance sustainability (BOC Seal Sands).
- Turquoise hydrogen: produced via methane pyrolysis, which takes place when a hydrocarbon fuel is thermally cracked into hydrogen and carbon. For example, when methane (CH_4) is heated to the required temperature, it spontaneously decomposes into carbon (C) and hydrogen ($2H_2$). The determining factor as to the environmental impact of turquoise hydrogen is the source of the heat being used, as well as the need for the carbon to be stored.
- Black and brown hydrogen: derived from black or brown coal (lignite), is an established process used in many industries that converts carbon-rich materials into hydrogen and carbon dioxide (CO_2) via coal gasification. If the CO_2 generated by the process is captured, then the hydrogen produced can be considered to be blue hydrogen. However typically the CO_2 generated is not captured, making it the most harmful method of generating hydrogen, especially when the emissions from the extraction and transport of coal are considered.

These types, with varying environmental impacts, are crucial for a shift towards cleaner energy and a net-zero future (National Grid, 2023) [12]. Each type has its distinct environmental footprint and technological requirements. For instance, green hydrogen production, which utilises renewable electricity, offers zero direct CO_2 emissions, setting it apart from its counterparts (Ishaq et al., 2022) [18] but uses significant quantities of water.

The cost of hydrogen production is a significant hurdle, particularly for green hydrogen. Production costs using steam reforming are about three times higher than natural gas per unit of produced energy. Similarly, electrolysis, a method for green hydrogen production, can cost twice as much as natural gas-based methods, depending on electricity prices (Ishaq et al., 2022) [18]. The study also mentions that the inclusion of infrastructure and storage costs, as well as the cost of raw materials such as water, indicates that the overall expenses could be more than twice and closer to four times or even higher in some scenarios.

The environmental impact of green hydrogen production is intricately tied to the electricity source used for powering the electrolysis. This impact becomes particularly pronounced when dealing with intermittent renewable energy sources like wind or solar, which may require adjustments in operating hours to optimise renewable electricity use. The efficiency of the conversion process, the capacity hours when utilising intermittent renewable energy sources, and the crucial requirement for grid inputs—potentially from the closest source, such as a natural gas-fired power station—are identified as critical factors that significantly affect both the efficiency and the environmental sustainability of green hydrogen production (Vilbergsson et al., 2023) [19].

The production of green hydrogen is notably more electricity-intensive compared to other low CO_2 hydrogen production technologies. Specifically, it requires over three times the green power than turquoise hydrogen (produced via methane pyrolysis) and over 37 times more than the conventional steam methane reforming process when combined with CCS. This high demand for green power places a significant emphasis on the sustainability assessment of green hydrogen production, especially considering the fluctuating availability and potentially high costs of renewable energy sources. Consequently, the cost of producing green hydrogen is generally higher compared to other low CO_2 hydrogen technologies, underlining the need for careful consideration of energy source sustainability and economic factors in its production (Hristescu, 2022) [20].

Liquefaction, storage, and transportation form a significant part of the green hydrogen production process, especially for long-haul transportation. Liquefaction, a process chosen for transporting hydrogen from locations like Iceland, is considered more environmentally friendly than alternatives such as transporting hydrogen as liquid organic hydrogen carriers (LOHC). However, in strategic long-term planning, transporting hydrogen via a gas grid network is viewed as the most economically and environmentally viable method, if feasible (Vilbergsson et al., 2023) [19].

In the future, the production of green hydrogen is expected to grow significantly worldwide. The European Union, for example, aims to produce 40 GW of green hydrogen by 2030. China targets 5 million tonnes of hydrogen per year by 2025, focusing on green hydrogen. Similarly, the United States plans to produce 5 GW of hydrogen by 2030, with a potential market size of up to USD 140 billion per year by 2050. Japan, Australia, and other countries also have ambitious targets and projections for green hydrogen production, driven by policy support, technological advancements, and the availability of renewable energy sources (Marouani et al., 2023) [21].

A study by Hauglustaine et al. 2022) [22], calculated the Global Warming Potential (GWP) of hydrogen over different time horizons, indicating significant potential climate impact depending on production and usage Hauglustaine et al. 2022) [22]. The climate impact is heavily dependent on hydrogen production pathways, with green hydrogen showing a beneficial impact, while blue hydrogen can lead to a climate penalty at high leakage rates. The study also highlighted the importance of managing hydrogen leakage rates during production, transport, storage, and use. A green hydrogen economy can significantly abate CO_2 emissions, but mixed scenarios with blue hydrogen, especially at higher leakage rates, reduce these benefits. The study underscores the need for careful consideration in planning and implementing a hydrogen-based energy economy.

Blue hydrogen is increasingly viewed as a transitional energy carrier in the move towards low-carbon economies. The production and environmental impact of blue hydrogen, however, are subject to various factors that influence its overall carbon balance and efficiency. Jane Durling (2021) [23] discusses various technologies associated with blue hydrogen production and these are summarised below. Each of these technologies is coupled with CCS to reduce CO_2 emissions.

- Steam Methane Reforming (SMR) - process uses methane and water to produce hydrogen. The methane is pre-treated, mixed with steam, and reformed. CO_2 produced in the process is captured post-combustion, compressed, dehydrated, and stored or used elsewhere. The hydrogen is then purified and compressed for distribution.
- Autothermal Reforming (ATR) - uses methane, water, and oxygen. It combines reforming with combustion, allowing the process to be autothermal. A CO shift reaction further increases hydrogen yield. The CO_2 is captured, and the hydrogen is purified and compressed.
- Gas Heated Reforming (GHR) - technique involves a two-stage process where methane and steam first enter a gas heated reformer, followed by an autothermal reformer with oxygen input. It’s potentially more efficient due to its staged nature and heat recovery.
- Partial Oxidation (POX) - methane is partially oxidised with oxygen and steam to produce hydrogen and CO. A CO shift reaction is employed, and the resulting CO_2 is captured. The hydrogen is then purified and compressed, ready for use.

Zhang et al. (2021) [24] highlighted the importance of integrating CCS in the hydrogen industry, particularly from technical, sustainability, and policy perspectives. It critically reviewed existing CCUS and hydrogen production technologies, discussing the feasibility of integrating CCUS in the hydrogen industry to accelerate carbon emission reduction by 2050. This integration, especially through CCUS+SMR (steam methane reforming), could significantly reduce emissions, pointing towards cleaner hydrogen production methods that mitigate health risks associated with fossil fuel-derived hydrogen.

Oni et al. (2022) [25] also describe the thermal decomposition of natural gas within a carbon capture and storage (NGD-CCS) facility. Natural gas enters a fluidised bed reactor, where it is thermally decomposed in the presence of a catalyst, resulting in the production of hydrogen and solid carbon. The heat from this reaction is captured for efficiency. Solid particles are then removed from the gas stream by cyclones. The remaining gas, primarily hydrogen, is purified through a pressure swing adsorption system. The hydrogen is stored for future use. Concurrently, CO_2 generated during the process is captured from the flue gases, compressed, and then transported for sequestration, thus reducing the environmental impact of the process.

The carbon balance in blue hydrogen production is closely associated with the consumption of natural gas feedstock, the use of electricity, and the overall efficiency of the CO_2 capture process. The amount of natural gas and electricity consumed significantly influences the environmental sustainability of blue hydrogen. Efficient CO_2 capture is crucial to minimizing the carbon footprint of this process. Recent studies have highlighted the importance of optimizing CO_2 capture to improve the environmental viability of blue hydrogen, suggesting that high capture efficiencies are necessary to reduce CO_2 emissions and natural gas consumption effectively (Romano et al., 2022) [26].

Leakage within the natural gas supply chain is another critical concern, as it significantly contributes to greenhouse gas emissions. Howarth and Jacobson (2021) [27] stated that the impact of fugitive methane emissions is critical in determining the overall greenhouse gas footprint of blue hydrogen production and when including the effects of methane leakage, 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) [26] point out that the methane leakage rates used by Howarth and Jacobson are higher than what is observed in many countries and can be reduced using existing technologies at low costs and concludes 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.

Therefore, minimising methane leakage is imperative to reduce the overall greenhouse gas emissions from blue hydrogen production. Moreover, the choice of metrics for quantifying the climate impact of methane emissions, particularly the Global Warming Potential (GWP), plays a significant role in evaluating the environmental impact. The GWP metric aggregates the impacts over time, requiring the specification of a time horizon, such as 100 years (GWP100) or 20 years (GWP20), for comparison.

In terms of carbon capture rates, technologies like SMR with amine units lead to a 52% CO_2 capture rate (referred to as SMR-52%), while including flue gas capture can increase this rate to 85% (SMR-85%). Autothermal Reactor (ATR) with CO_2 capture can achieve a 91% capture rate, and Natural Gas Decomposition (NGD) with CO_2 capture reaches a 61% capture rate (Oni et al., 2022 [25]; Bauer et al., 2022 [28]). The different carbon capture rates indicate the efficiency with which CO_2 is captured and removed from the process stream. A SMR system with an 85% capture rate would be more efficient and as a result, emit less CO_2 than the one with a 52% capture rate.

These variations highlight the importance of technology and process design in blue hydrogen production. Regarding energy consumption, natural gas and electricity remain the primary energy sources for hydrogen production. For instance, SMR-85% consumes the most natural gas per kg of hydrogen produced, primarily due to its high demand for low-pressure steam in amine regenerators. The consumption pattern of natural gas as feedstock and fuel varies across different technologies, with ATR consuming the least fuel per unit of hydrogen produced due to the heat recovered from the autothermal reactor (Oni et al., 2022 [25]; Bauer et al., 2022 [28]).

Bauer et al. (2022) examined carbon capture configurations in hydrogen production plants, focusing on two configurations described as "CCS-low" and "CCS-high." Both used methyl diethanolamine (MDEA) as the solvent for capturing CO_2. The "CCS-low" configuration captured 55% of CO_2 emissions and corresponded to an SMR process with a high-temperature water-gas shift and 90% capture rate from the syngas. The "CCS-high" represented an ATR process that captures up to 98% of CO_2 from the syngas, leading to a plant-wide capture rate of 93%.

The greenhouse gas emissions associated with blue hydrogen production are also varied. The highest emissions are observed in SMR without CCS, while the lowest are in ATR with CCS. The on-site emissions from the combustion of natural gas as fuel contribute significantly to the overall carbon emissions, especially in cases without CCS. The application of CCS, while reducing on-site emissions, increases upstream emissions associated with electricity and natural gas required for the amine regenerator.

Wang et al. (2007) [29] explored the air quality impacts of hydrogen production and delivery, particularly through SMR. It compares different hydrogen supply pathways, including onsite production, centralised production with pipeline delivery, and centralised production with liquid truck delivery. The study concludes that all pathways have a low impact on air pollution, with centralised pipeline delivery being the most effective in minimising pollution, followed by on-site hydrogen production (Wang et al., 2008) [30].

However, a key consideration is the impact that hydrogen leakage may have in terms of climate change. While increased hydrogen use could lead to reductions in CH_4, CO, NO_x, and VOCs (Warwick et al., 2022) [31] 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. Specifically, the challenges posed by hydrogen's molecular properties are pronounced at critical points in the hydrogen infrastructure, such as transportation systems, gaskets, joints, and seals.

Hydrogen leakage is a concern for global warming and could influence the distribution of methane and ozone. Ocko and Hamburg (2022) [32] focused on the indirect greenhouse gas effects of hydrogen, particularly its warming impact. They revealed that hydrogen while being a low-carbon energy source, has indirect warming effects due to leakage into the atmosphere. This study used advanced climate modelling to assess these effects and emphasised the importance of considering hydrogen emissions in climate change mitigation strategies. The study by Van Ruijven et al. (2011) [33] provides a range of hydrogen leakage rates across different components of the hydrogen supply chain (i.e., transport, distribution, and end-use).

Transporting hydrogen over long distances, particularly by sea, can lead to significant energy losses and potential hydrogen emissions to the atmosphere. For example, a 2,400 km sea journey might incur energy losses of around 4.8%, with possible atmospheric emissions of 2-3%. Liquid hydrogen transport by truck or train can suffer from boil-off losses during transfer, typically between 3% and 5%. Pipelines specifically designed for hydrogen can have very low leakage rates, but repurposed natural gas pipelines could see leakage rates escalate dramatically. Storage of hydrogen in liquid form also faces daily boil-off challenges, leading to considerable cumulative losses over time. During usage in fuel cells, operational emissions, though typically small, do occur.

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%. These findings emphasise the need for careful system design and operation to minimise hydrogen leakage and maximise efficiency.

The potential hydrogen leakage rates at various stages of hydrogen production, including SMR with carbon capture, coal and bio-gasification with carbon capture, and electrolysis, are important aspects of understanding the environmental impact of hydrogen production. Research suggests that loss rates from electrolysers could be high. Frazer-Nash Consultancy (2022) [34] identified three main hydrogen emission mechanisms for electrolytic hydrogen production: venting at startup and shutdown, venting due to hydrogen cross-over (i.e., the phenomenon where hydrogen molecules pass through the electrolyte from the anode to the cathode side without contributing to the external circuit's current flow), and operational purging as part of the purification process. However, venting during start-up and shutdown can contribute to emissions, ranging from 0.05 to 0.6%. These emissions are influenced by the duration of the start-up/shutdown sequence and the number of such events per year. Additionally, hydrogen crossover, which refers to the venting of oxygen, can lead to emissions of 0.05 to 0.15%, dependent on the minimum production capacity and the proportion of hydrogen that is recombined to produce water.

Purging processes to remove impurities represent another significant source of emissions, potentially contributing 0 to 10% of hydrogen emissions. The rate of emissions from purging is affected by the amount of vented hydrogen during operation and the efficiency with which vented hydrogen is recombined into water. Additionally, due to hydrogen's small molecular size, the transportation of hydrogen is likely a major source of leakage. Fluid dynamics theory suggests that hydrogen can leak 1.3 to 3 times faster than methane. The total value-chain emissions depend on the configuration of the pathway from production to end use. Previous studies have estimated hydrogen emissions ranging from 0.3% to 20% for minimum to maximum emissions.

For blue hydrogen production, methane is used both as a feedstock and a heat source. Methane emissions can occur along the supply chain before it is utilised for producing hydrogen. The amount of methane needed for hydrogen production depends on the natural gas composition, the efficiency of the reformer, and the total amount needed for both feedstock and fuel. It can range from 2.5 to 4.5 times the mass of the hydrogen produced. Methane emission estimates include venting, purging, and flaring upstream of hydrogen production. The latest understanding of upstream natural gas leakage suggests a range of 1% (best case) to 3% (worst case) per unit of methane consumed.

According to Esquivel-Elizondo et al. (2023) [35], field measurements of hydrogen emissions from production to end-use, are needed to assess its climate impact accurately. In their study, they found that the estimated emission rates vary depending on the method. For grey hydrogen, emissions range between 0.5% and 1.0%, while for blue hydrogen, they range from 0.0% to 1.5%. Green hydrogen production, often involving electrolysis, can have higher emission rates, ranging from 0.03% to 9.2%, partly due to the higher emissions associated with the electrolysis process compared to other methods like steam methane reforming and biomass gasification. Liquefaction, liquid hydrogen transporting and handling, and refuelling processes have the largest ranges of emission rates, between 0.15% to 10% for liquefaction, 2% to 20% for handling, and 2% to 15% for refuelling. These rates illustrate the variability and potential environmental impact associated with hydrogen infrastructure and logistics (Esquivel-Elizondo et al., 2023) [35]. Overall, total hydrogen emissions rates across its entire value chain are estimated to be between 0.2% and 20%, underscoring the importance of considering the entire hydrogen lifecycle in environmental impact assessments.

3.1.3 Hydrogen's role in a cleaner future

The importance of hydrogen production is reflected by the global shift towards sustainability and reduced carbon emissions that has ushered in an era of innovation and transition in energy systems. Among these, hydrogen emerges as a beacon of hope for decarbonising various sectors, including transportation and industry.

The Tees industrial cluster, a pioneering region in the UK's efforts to embrace low and zero-emission technologies, serves as an exemplary case study in this transformative journey. This analysis delves into the multifaceted aspects of hydrogen technology adoption, from the combustion of hydrogen and its implications for bulk storage, NH_3 cracking at fuel stations, to the distinctions between green and blue hydrogen. It also examines the Tees-wide hydrogen distribution system, hydrogen's role as a raw material for sustainable aviation fuel (SAF), and critically, the emissions resulting from hydrogen fuel cell use. Through a synthesis of current research and numeric results, this paper aims to illuminate the environmental impacts and technological pathways associated with hydrogen's rise as a dominant fuel of the future. As the Tees cluster embarks on this ambitious path, understanding the nuances of hydrogen technology becomes paramount in ensuring that this transition not only meets economic and energy security goals but also aligns with global environmental and sustainability objectives.

3.1.4 Hydrogen Technologies Overview

Bulk Hydrogen Storage: NH_3 is recognized as an efficient hydrogen carrier due to its high hydrogen density, facilitating bulk storage. The theoretical hydrogen conversion efficiency from NH_3 is about 90%, making it advantageous for large-scale storage and transportation [36].

NH_3 Cracking at Fuel Stations: Solid-oxide fuel cells can effectively convert NH_3 back to electricity, showcasing NH_3 potential as a sustainable fuel, especially for on-site hydrogen production at fuel stations [37].

Hydrogen Distribution System: The development of a comprehensive hydrogen distribution system, including manifolded distribution networks, is essential for the widescale adoption of hydrogen technologies. Such systems must efficiently transport and distribute hydrogen to various points of use, including industrial applications and fuel stations.

Hydrogen for SAF Production: Utilising hydrogen as a raw material for sustainable aviation fuel (SAF) production presents a promising avenue for reducing aviation sector emissions. This approach involves converting hydrogen, along with captured CO_2, into SAF through processes like Fischer-Tropsch synthesis.

3.1.5 Emissions from Hydrogen Fuel Cell Use

Hydrogen fuel cells (HFCs) offer a promising path towards decarbonising various sectors, notably transportation. Unlike internal combustion engines, HFCs produce water vapor as their primary byproduct, significantly reducing pollutants such as volatile organic compounds (VOC), carbon monoxide (CO), NO_x, PM_{10}/$PM_{2.5}$, sulphur oxides (SO_x), and CO_2. A potential environmental impact of hydrogen fuel cells is the unintended emission of molecular hydrogen, which can increase the abundance of water vapour in the stratosphere by approximately 1 part per million by volume. This could lead to stratospheric cooling, enhancement of the heterogeneous chemistry that destroys ozone, an increase in noctilucent clouds, and changes in tropospheric chemistry and atmosphere-biosphere interactions (Tromp et al., 2003) [38].

A study compared emissions from internal combustion engine vehicles, hybrid vehicles, and fuel cell vehicles using hydrogen in gas or liquid form. It was found that gaseous hydrogen-powered fuel cell vehicles appear to be the best option, reducing CO_2 emissions significantly compared to liquid hydrogen-powered vehicles and traditional gasoline vehicles. For example, the lowest CO_2 emission values for gaseous hydrogen-powered fuel cell vehicles in 2050 were observed to be 81 g/km, a stark contrast to 416 g/km for liquid hydrogen-powered spark ignition internal combustion engine vehicles in 2010 (Uguru, 2020) [39].

3.1.6 Potential Future Impacts

Dillman and Heinonen (2023) [40] raised concerns about climate overshoot, with emissions potentially exceeding the safe space for greenhouse gases by 5.4–8.1 times by 2050. The cumulative carbon budget consumption of the hydrogen economy could be 8–12%. The study highlights challenges with blue hydrogen, which, despite being cleaner, faces difficulties in reducing emissions effectively. It might become environmentally unviable between 2025 and 2035. Green hydrogen, produced through electrolysis using renewable sources, is cleaner but requires substantial renewable energy and vast quantities of water, impacting land and material use.

The study suggests the importance of demand-side solutions and the need for science-based definitions of "clean" hydrogen. It also discusses the implications of green hydrogen on electricity generation and land use, emphasising the need for a comprehensive approach that includes behavioural changes and efficiency improvements.

A study by Sand et al. (2023) [41] showed the 100-year Global Warming Potential (GWP100) of hydrogen to be 11.6 ± 2.8. Hydrogen affects the climate due to its indirect impacts on gases like methane, ozone, and stratospheric water vapour. The major contributors to its GWP100 are changes in methane, ozone, and stratospheric water vapour. The study highlights the importance of reducing hydrogen leakages and addresses uncertainties in estimating the GWP100, particularly concerning soil sink estimates. It suggests that future work should focus on better understanding these uncertainties and exploring the influence of changes in other atmospheric components.

3.2 Carbon Capture

Carbon Capture (CC) technologies are one of the pivotal technologies within the Tees Industrial Cluster to help in mitigating CO_2 from a wide variety of industrial processes and power generation. It is one of the significant contributions to decarbonisation ambitions from the cluster. It will be developed on technologies that were originally developed for improving the quality of natural gas but have since evolved to find broader applications and are illustrative of the integrative nature of all processes associated with carbon management in the cluster.

The Tees Cluster has identified a diverse set of processes and projects for CC technology application, including:

- Carbon Capture on Power Generation: As a whole, the focus was laid based on units operating at small to large scales for overall emission.
- Waste tyres to Sustainable Aviation Fuel (SAF): Using CC to reduce the carbon footprint from the process of converting waste tyres to SAF (Wright and Lewis, 2022) [8].
- Existing Grey Hydrogen Production: Grey hydrogen facilities are augmented by the CC to cover the by-product CO_2 emissions coming from SMR (Dutka et al., 2016) [4].
- Energy from Waste (EfW) Enhancements: Enhancements through retrofitting and integrating CC in both existing and new EfW plants to sequester CO_2 generated from waste combustion.
- Biomass Processing and Conversion: CC technology can be used during the change of use of biomass into energy or other usable products to capture emissions.
- The processes of lithium refinery: adoption of CC in lithium processing to manage emissions, a must for the sustainability of battery production.
- Waste to Alternative Fuels and Biomass to Alternative Fuels: Using CC to convert non-recyclable waste and biomass into cleaner fuel alternatives.

Operations of electric arc furnace (EAF) steel production: the implementation of carbon capture (CC) technologies significantly minimises the impact of greenhouse gases for the iron and steel industry. 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.

The British Steel initiative for constructing a new electric arc furnace (EAF) at Lackenby in Redcar, which applied for planning permission in December 2023, represents an important step forward in environmentally conscious industrial advancements. The application aligns with the UK's commitment to modernise traditional industrial practices to meet stringent environmental standards. The benchmark emissions values from EAF activities, as outlined in the Environment Agency's Sector Guidance Note IPPC s2.01 [42], are significant. For instance, primary fume particulate emissions from EAF are benchmarked at 20 g/t LS with existing plants expected to stay under 15 mg/m³ (daily means) and new plants under 10 mg/m³ hourly average, as per the UK experience. In terms of gaseous emissions, EAF operations are listed with benchmarks of 120-240 g/t for NO_x, while CO emissions range from 0.74-3.9 kg/t LS. The management of such emissions is critical to minimising the environmental impact of steel production processes [43].

SO_2 emissions from one German EAF plant were reported at 24-130 g/t LS, emphasising the importance of controlling and reducing such emissions in line with best available techniques. Moreover, the guidance addresses the potential release of complex compounds such as polychlorinated dibenzo-p-dioxins and furans (PCDD/F) and polycyclic aromatic hydrocarbons (PAHs), with the EAF stack emissions for PCDD/F expected to range between 0.07-0.9 µg I-TEQ/t LS, and EAF operations for PAHs benchmarked at 3.5-71 mg Σ EPA16/t LS (IPPC, 2004) [43].

The integration of PCBs emissions from the preheating of scrap steel in EAFs into the UK's Multi-Media Emission Inventory under the Stockholm Convention underlines the complexity and necessity of robust monitoring frameworks for these substances (Shen et al., 2021) [44]. Such emissions must be continuously monitored and managed to ensure compliance with environmental regulations and to safeguard public and ecosystem health.

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 has subsequently been improved using CC.

Similarly, the application of Ensus Plant CC and SABIC's approach to CO_2 capture from hydrogen production off-gas remains an outstanding example of how CC technologies could be applied in practice for the reduction of the carbon footprint from the chemical manufacturing process. Together with the comprehensive list of proposed CC applications, these detailed examples paint a vivid picture of the integrated and comprehensive strategy of the Tees Industrial Cluster for forward-looking carbon management. The cluster would like to be a world leader in the application of CC technologies across its different sectors, from power generation to waste management, steel production, and biofuel creation. The sectors that lead in this ambition would mean not just a substantial reduction in CO_2 but a way to set real leadership in the world for transitioning into a more sustainable, low-carbon future.

3.2.1 Carbon Capture Solvents

Amines, a group of organic derivatives of NH_3, are commonly employed in carbon capture (CC) systems to absorb CO_2. This absorption occurs when CO_2 reacts with amine-based solvents in an absorber, a key unit of the carbon capture process. However, the use of amines also raises concerns about environmental and health risks. 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, which have been associated with potential adverse effects on both health and the environment [45] [46] [47]. Amine-based carbon capture technologies are recognised for their critical role in mitigating global warming by capturing CO_2 emissions from fossil fuel combustion, a major contributor to climate change.

Studies by Puxty et al. (2009) [48] and Sanz-Pérez et al. (2016) [49] highlight the importance of improving the efficiency of amine absorption processes and the potential of amine-based sorbents in direct air capture (DAC) as strategies to significantly reduce greenhouse gas concentrations in the atmosphere, thereby contributing to global climate change mitigation efforts (Puxty et al., 2009 [48]; Sanz-Pérez et al., 2016 [49]).

Amines, when used in carbon capture (CC) processes, are emitted into the atmosphere [50] where they can undergo reactions with radicals, and NO_x. These reactions can lead to the production of various compounds, including nitrosamines and nitramines. However, it's important to note that not all amines form stable nitrosamines; for example, MEA is claimed not to form stable nitrosamines in the atmosphere. Additionally, the degradation of solvent systems in CC processes can lead to the release of other amines and solvent degradation products, including nitrosamines, into the air as direct emissions [51].

Given the complex and varied behaviour of different amines, it's crucial to comprehensively assess the emissions and environmental reactions associated with amines as a chemical group. This approach ensures a broader understanding of their potential impacts while acknowledging that individual amines like MEA or Diethanolamine (DEA) may have specific characteristics and effects. By adopting this comprehensive perspective, we avoid the pitfalls of oversimplification 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 significant environmental and health challenges due to the formation and release of toxic N-amines (i.e., a broad category of nitrogen-containing amines, including nitrosamines and nitramines, known for potential health risks) (Nielsen et al., 2012 [52]; Spietz et al., 2017 [53]; NEA, 2022 [54]; AECOM, 2017 [55]) which are known carcinogens.

NH_3 and other degradation products from amine-based carbon capture technologies not only potentially impact air and water quality but may undergo further transformations in these environments, complicating their ecological and health impacts. These complexities underscore the imperative for meticulous management and monitoring of carbon capture technologies to mitigate their environmental footprint effectively. Amines themselves, rather than their degradation products N-amines, are likely to pose little risk to human health and their emissions potentially contribute to nitrogen deposition and subsequently acid deposition. Main amine photo-oxidation products include nitrosamines, nitramines, aldehydes, and amides. Knusden et al. (2009) [56] mentioned the emissions of amine-based degradation products are of particular concern due to their toxic and carcinogenic properties at extremely low levels. Nitramines, though less potent than nitrosamines, are suspected carcinogens with a suggested longer lifetime in the atmosphere, potentially leading to higher exposure values.

For a full-scale gas-fired power plant capturing 1 million tonnes of CO2 per year, the estimated amine emissions range from 40-160 tonnes per year. This level of emissions necessitates thorough investigation and management to mitigate potential environmental and health impacts.

The Tees Estuary is facing environmental pressures, including excess nitrogen. While exploring carbon capture technologies for environmental benefits, it’s vital to ensure they do not add to these challenges (EA, 2023) [57].

The Teesmouth and Cleveland Coast SPA is a critical habitat for a diverse assemblage of bird species and encompasses various sensitive ecosystems like salt marshes, mudflats, and saline lagoons. Nitrogen deposition from amine emissions contributes to acid deposition, which could further deteriorate the SPA's condition, affecting the biological integrity of these habitats. Elevated nutrient levels, particularly nitrogen, can lead to eutrophication - an over-enrichment of water bodies with nutrients-, leading to excessive growth of algae and other aquatic plants. This process can disrupt the balance of ecosystems, leading to oxygen depletion and harm to aquatic life. The SPA/Ramsar site in the Tees area has been assessed as at risk of eutrophication, suggesting that additional nitrogen inputs from amine emissions could pose significant ecological risks.

Addressing these environmental concerns involves regulatory and management strategies that balance industrial activity with ecological preservation. The target for nutrient levels in the Teesmouth and Cleveland Coast SPA emphasises the need for restoring water quality to safe levels. However, achieving this could entail setting stringent permit limits for industrial sites and sewage treatment works, which could be costly and potentially impact industrial activities and future developments in the area.

While studies have shown that emissions of MEA and other amine-based degradation products can be very low under controlled conditions, the sensitive nature of the Tees Estuary ecosystem necessitates stringent monitoring and management. Even low-level emissions could have significant cumulative impacts over time, particularly in terms of contributing to nitrogen levels and exacerbating eutrophication.

Wurtsbaugh, et al. (2019) [58] explored how agricultural, urban, and industrial activities have increased aquatic nitrogen and phosphorus pollution, leading to eutrophication. They discussed the need for dual nutrient control strategies and highlighted the challenges in managing this global environmental problem, emphasising the significant role of low-level nitrogen emissions in eutrophication processes.

Atmospheric dispersion models, including preliminary results from studies conducted at both lab-scale and in operational facilities like the CO_2 Technology Centre Mongstad (TCM DA), demonstrate that amine emissions impact air quality at local and regional scales. These models and empirical studies, covering a range from lab experiments to pilot plant operations, reveal that emissions of monoethanolamine (MEA) are significantly low, measured in parts per billion (ppb). Similarly, emissions of amine-based degradation products, including nitrosamines and nitramines, were found to be below detectable levels in the atmosphere, indicating efficient mitigation strategies at these scales. NH_3 emissions, however, were detected in the low parts per million (ppm) range in pilot plant studies, suggesting the need for controlled conditions to manage amine emissions effectively [59] [60]. This comprehensive approach, combining modelling with empirical data from facilities like TCM DA and pilot plants using aminoethylethanolamine, underscores the importance of scale in assessing and managing the environmental impacts of amine emissions in carbon capture processes (Morken et al., 2014 [61]; Spietz et al., 2017 [53]; Buvik et al., 2021 [62]; Pakchotanon et al., 2022 [63]).

While there are some methods and studies related to the monitoring of amines and N-amines, particularly nitrosamines and nitramines, there is a global lack of standardised reference methods, especially for stationary source emissions. Instead, various occupational health methods from the U.S. are employed, utilising ThermoSorb/N cartridges for sampling. Studies on nitrosamines in post-combustion carbon capture installations show a lack of uniform methodologies, with most detections near or just above the limit of detection (Ellison et al., 2022 [64]).

The issues surrounding monitoring/measuring amines and N-amines are complex due to the lack of standardised global methodologies. While some countries have initiated specific monitoring practices, there isn't a cohesive, international approach. For instance, Norway's TCM Mongstad and Denmark's Esbjerg Power Station employ advanced techniques like FTIR and PTR-MS (Flo et al. 2017 [65]; Morken et al., 2014 [61]). However, these instances are not indicative of a global standard, and many countries lack routine sampling protocols. This results in a significant gap in baseline data worldwide, hindering a comprehensive understanding of the environmental impact of these emissions. Efforts to develop new methods, like impinger-based and Thermosorb cartridge methods, are underway but not yet standardised (Ellison et al., 2022 [64]).

The use of amine-based technologies in carbon capture presents potential occupational risks, especially since no occupational safety limits have been established for acute or chronic exposure to amines specific to CCS facilities. This lack of established limits highlights significant knowledge gaps in ensuring worker safety and health in CCS facilities. A study conducted by Gentry et al. (2014) [66] identified major risks and hazards associated with amine-based carbon capture at their Kingsnorth coal- and oil-fired power plant, emphasising the potential exposure of workers to amines or amine-degradation by-products through inhalation and dermal contact.

Amines used in CCS, absorbed by oral, dermal, and inhalation routes, generally exhibit low acute systemic toxicity. However, concentrated alkanolamine solutions can cause local eye, respiratory, and skin irritation. MEA and DEA have been identified as skin sensitisers in some instances, particularly following prolonged dermal exposure. Brekke et al. (2012) [67] in their assessment, highlighted that the Human Toxicity Potential is significantly affected by CCS technology, often showing an increase of nearly 200% in systems with CCS. Chronic exposure to amines like MEA and DEA can lead to systemic toxicity, with DEA showing accumulation in selected tissues and potential effects on phospholipid metabolism. Chronic inhalation of MEA vapours at high concentrations has been associated with neurological effects.

Regarding carcinogenicity, extensive research on DEA has shown clear evidence of carcinogenicity in mice, suggesting an epigenetic mode of carcinogenesis involving intracellular choline deficiency (Gentry et al., 2014) [66]. Nitrosamines and nitramines formed in CC plants have been classified by the International Agency for Research on Cancer (IARC) as Group 2A (probably carcinogenic to humans) and Group 2B (possibly carcinogenic to humans). These substances are known for their potential carcinogenic and mutagenic properties (Spietz et al., 2017) [53].

A small proportion of amine solvent and degradation products escape from the absorber and are released into the atmosphere along with the cleaned flue gas. This release can cause environmental damage, contaminating soil and groundwater (Spietz et al., 2017 [53]; Jablonka et al., 2023 [68]; Nielsen et al., 2012 [52]; Azzi et al., 2014 [69]). Mist formation in the absorber, caused by fine water droplets, is also a concern for amine emissions (Spietz et al., 2017 [53]). These fine droplets not only complicate emissions monitoring at the stack exit, making compliance with regulatory standards more challenging but also increase carry-over, underlining the importance of effective containment and mitigation strategies. Such challenges and solutions are elaborated within the framework of post-combustion Best Available Techniques Reference Document (BREF) guidelines, which emphasise the necessity of addressing both the environmental impacts of amine emissions and the operational complexities introduced by fine droplet formation to ensure regulatory compliance and minimise environmental risks (European Commission, 2017 [70]).

A comprehensive understanding of these emissions and their impacts is essential for developing effective management and mitigation strategies.

3.2.2`Emerging Carbon Capture solvents and innovative approaches

The landscape of CCS technology is rapidly evolving with the development of new solvents and innovative approaches, each offering unique benefits in the quest to mitigate climate change. These advancements, ranging from specialised solvents like CESAR-1 and OASE blue to natural processes such as algae-based bio-fixation, represent the diverse strategies being employed to address the growing concerns of atmospheric CO_2 levels. CESAR-1 and OASE blue, developed through collaborative efforts and extensive research, have demonstrated significant improvements over traditional solvents like MEA in terms of efficiency, energy requirements for regeneration, and reduced degradation rates. On the other hand, the use of algae, particularly microalgae, in CCS presents a more natural approach, due to their efficient bio-fixation capabilities to capture and utilise CO_2. These advancements in CCS technology, including the exploration of ionic liquids with their unique properties for CO_2 capture, reflect the ongoing efforts to find more effective, economical, and environmentally sustainable solutions for reducing global carbon emissions.

To further enhance the efficacy and adoption of these technologies, it is crucial to establish a transparent method for sharing information on solvent CO_2 capture rates, energy efficiency, and water use. This approach will move the industry swiftly towards the Best Practicable Environmental Option (BPEO), ensuring that advancements in CCS technology are effectively contributing to the reduction of global carbon emissions. Standardised reporting on these parameters will facilitate the comparison and evaluation of emerging technologies, promoting best practices in CCS implementation and supporting the global effort to mitigate climate change.

CESAR-1

CESAR-1, an innovative solvent for CCS, comprises of 2-amino-2-methyl-propanol (AMP) and piperazine (PZ), offering substantial improvements over the traditional Monoethanolamine (MEA) [71]. Its application in post-combustion CO_2 capture, particularly in advanced supercritical (ASC) coal power plants, demonstrates significant advantages due to higher CO_2 concentrations in the flue gas. As per Fernandez et al. (2014) [72], CESAR-1 notably reduces the power production penalty in both coal (by 25%) and gas-fired (by 12%) plants compared to MEA. Additionally, it exhibits a lower rate of efficiency reduction, indicating better overall performance. Its degradation rates are also favourable; with AMP showing about half the degradation rate of MEA and piperazine noted for its stability, this translates into less frequent solvent replenishment and potentially lower operating costs despite the higher cost of the amines (Manzolini et al., 2015 [73]).

In terms of thermal energy and regeneration, CESAR-1 is more efficient, requiring less energy than MEA, which is crucial for CCS sustainability. According to the 16th International Conference on Greenhouse Gas Control Technologies GHGT-16 (2022) [74] [75], CESAR-1 achieves about 91% CO_2 capture with lower specific reboiler duties. While assessing environmental impact, measures of formaldehyde, acetaldehyde, and acetone emissions were considered, emphasising the environmental safety of CESAR-1. However, its economic viability is challenged by higher operating costs due to the expensive amines, despite the benefits of reduced efficiency penalties and better thermal performance (Fernandez et al., 2014 [72]; Manzolini et al., 2015 [73]). The solvent's higher resistance to degradation could, however, positively influence the overall cost-effectiveness in the long term.

OASE Blue

OASE blue solvent, developed by BASF in collaboration with RWE and Linde is characterised by the manufacturers as offering enhanced performance, lower energy requirements for regeneration, reduced degradation rates, and lower capital and operating costs. This technology, aimed at modular carbon capture solutions, is versatile for various flue gas sources, including coal-fired power plants, and focuses on cost savings and sustainability [76].

The solvent has demonstrated efficient CO_2 capture, with over 55,000 hours of testing under real power plant conditions [77]. Regarding energy consumption, the solvent surpasses the DOE benchmark, consuming 7% less energy for solvent regeneration. Economically, it offers substantial reductions in capital expenditure and is suitable for various scales of CO_2 capture and storage, including Enhanced Oil Recovery (EOR) and smaller-scale applications. Its advanced process concepts and specific energy demand reduction by 20% make it more economically viable across a broad range of applications (4th Post-combustion Capture Conference, 2017 [78]; GHGT-15, 2021 [79]).

Algae

Algae-based carbon capture is an emerging approach distinct from traditional methods like CESAR-1 and OASE blue. Unlike conventional CCS methods that store CO_2 underground, algae, particularly microalgae, utilize CO_2 through bio-fixation. These algae are efficient in capturing CO_2, with rates ranging from 159-178 mg/L/day and up to 96% CO_2 consumption efficiency. This high efficiency is attributed to their ability to thrive in extreme environments and utilise waste gases such as CO_2, NO_x, and SO_x from flue gas. Algae can be integrated into CCS systems, capturing CO_2 emissions from industrial sources and using them for growth, effectively removing CO_2 from the atmosphere (Singh and Dhar, 2019 [80]; Beal et al., 2018 [81]).

Algae offers several advantages for sustainability and economic value [82] [83] [84]. They don't require arable land for cultivation, making them an environmentally sustainable option. They can produce various economically valuable products, including bioenergy, animal feed, and bioproducts, surpassing other feedstocks in CO_2 capture efficiency (Beal et al., 2018 [81]). However, achieving economic viability in algae cultivation is challenging due to high capital costs and the need for efficient resource sourcing. Innovations like integrating algae production with bioenergy carbon capture and storage (BECCS) are promising in reducing costs and increasing efficiency. Algae cultivation not only reduces atmospheric CO_2 but also produces valuable biomass for various applications, presenting a sustainable method for climate change mitigation and economic benefits. Microcapsules are being explored to deliver CO_2 more efficiently to algae cultures, potentially saving significant costs in algae cultivation (Ralph and Pernice, 2023 [85]; Beal et al., 2018 [81]).

Ionic Liquids

Ionic liquids (ILs) hold the potential for CO_2 capture ($SELCO_2$). There are two types: protic ionic liquids (PILs) that can donate a proton and aprotic ionic liquids (AILs) that cannot. The characteristics of ILs, including their anion properties, free volume, molecular weight, and interactions, determine their effectiveness in CO_2 capture. ILs are generally denser than water but some exceptions exist with densities ranging from 0.90 to 0.97 g/cm^3. Increasing temperature tends to decrease the density of ILs. The composition of the flue gas, especially the CO_2/N_2 ratio, significantly affects $SELCO_2$. Different ILs have varying selectivity for different gas components (e.g., CO_2/H_2, CO_2/CH_4) and their performance depends on temperature. The suitability of an IL for CO_2 capture depends on the specific composition of the gas stream to be treated.

C-Capture

The Carbon Capture Solvent Compatibility Unit (CCSCU), in partnership with Singleton Birch, underwent a detailed analysis of its emissions and operational efficiency for the fourth quarter of 2023 (C-Capture, 2024) [86]. This period, spanning from November 2023 to January 2024, highlighted the CCSCU's performance in capturing CO_2 from flue gas emissions. With a focus on the CO_2 and water vapour concentrations in the flue gas inlet stream from Singleton Birch’s Kiln 2, average levels were recorded at 19.18 vol% for CO_2 and approximately 0.67 vol% for water vapour. These metrics provide a baseline for understanding the gas treatment process and underscore the importance of monitoring operational variables, such as the kiln's cyclic operations and downtime, which influence CO_2 concentration variability.

A significant portion of the report is dedicated to the emissions analysis of acetaldehyde and formaldehyde, which are byproducts of the carbon capture process. Given their potential health impacts, the EALs for these compounds are stringently set at 5 $\mu g/m^3$ for formaldehyde and 370 $\mu g/m^3$ for acetaldehyde. The trial's findings revealed that the concentrations of these aldehydes were substantially below the EALs, indicating minimal health risks. Specifically, formaldehyde and acetaldehyde concentrations at the absorber outlet averaged at 0.1ppm (0.132 mg/m^3) and 1.5ppm (2.91 mg/m^3), respectively. These values, when considering the flue gas flow rate and atmospheric dilution factors, translate to expected atmospheric concentrations of 9.61 ppt for formaldehyde and 0.14 ppb for acetaldehyde. The total emissions were estimated at 408.54 mg of formaldehyde and 9 g of acetaldehyde over the trial period.

The C-Capture CCSCU EA Q4 2023 Emissions Report SB-CCL Trial concludes that the emissions of formaldehyde and acetaldehyde from the CCSCU operation are significantly below harmful levels, posing little to no risk to human health. This analysis reinforces the environmental safety of the CCSCU process and supports the ongoing development and implementation of carbon capture technologies.

3.2.3 Infrastructure for CCS and Hydrogen Distribution

In addition to the discussed benefits and challenges of hydrogen production, it is essential to consider the infrastructure required for CO_2 and H_2 management. This includes the necessity for on-site polishing of CO_2 to meet new pipeline specifications, ensuring compatibility with storage and transport requirements. There is, therefore, the possibility of concentrated CO_2 to be vented during start-up and shutdown operations, especially if operating as dispatchable plants, and maintenance periods. These cases are illustrative of the required firm relevance of undertaking strength in both maintenance procedures of the CO_2 pipelines and emergency response strategies.

Further, concerning the allocation of such space within the pipeline CO_2 network, often on a 'first come, first served' basis, the matter does raise concerns in the light of potentially blocking new projects in the future. In other words, this should equally comprise an equitable and strategic plan to ensure that pipeline infrastructure for CO_2 capture and storage projects of today and tomorrow is adequate.

There is the potential for CO_2 and hydrogen emissions from transportation [87] and storage [88]. Further, in any case of spill or leakage, the heavier-than-air property of liquid CO_2 would, therefore, require proper risk assessment and mitigation strategies for not only avoiding but also controlling CO_2 ponding. With the above, therefore, the Tees-wide hydrogen distribution pipeline development becomes very instrumental in allowing the support to the differentiated needs of green and blue hydrogen markets.

This could, therefore, reflect market dynamics, whereby select consumers could even be willing to pay a premium for green hydrogen, allowing separate pipelines of green and blue H_2 to be available to provide certainty of the source to the consumer to be able to select the type fitting his needs.

Bulk storage of hydrogen comes along with a set of challenges, including flaring, fugitive emissions, and venting, and the environmental impacts of hydrogen, e.g. is ability to act as a secondary greenhouse gas [89, 90]. These require that there be quality metering points and monitoring standards to meet hydrogen pipeline tripartite challenges of safety, efficiency, and environmental compliance. These developments in infrastructure may duly address stakeholders for integrating efficiently side by side with carbon capture and storage technologies into the wide scale of energy and environment.

3.2.4 Impact of climate on Carbon Capture technologies

The various climate conditions, especially temperature and humidity, have the potential to affect the performance of solvent-based systems, including CC technologies. The CO_2 capture rate is significantly influenced by air temperature and relative humidity. Capture efficiency varies greatly depending on these conditions.

A study by An et al. (2022) [91] 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 instance, a CO_2 capture rate of 75% is only possible above 17°C and 90% relative humidity. Consequently, 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. Moreover, water demand depends on the relative rates of water evaporation and generation in the air contactor, which are also influenced by climate conditions. They found that net water loss is higher in hot and dry conditions, which could impact the deployment of liquid solvent-based DAC in such geographical locations. Conversely, in cold and dry locations where temperatures drop well below 0°C, net water loss is lower, but CO_2 capture rates also decrease, potentially increasing energy demand. The studies emphasised 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) [92] investigated how rising ambient temperatures affect the performance and water use of natural gas and coal power plants and highlighted that higher ambient temperatures led to increased pressure at the steam turbine outlet, and thus decreasing plant efficiency.

With regard to the impact on amine regeneration in CC technologies, warmer weather can present challenges as well. 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. Furthermore, the implementation of environmental regulations, such as the European Eel Regulation, is increasingly restricting the extraction of cooling water from estuaries or the sea, impacting the availability of a critical resource for managing temperatures in the amine regeneration process (European Commission, 2007) [93]. 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 could be optimised, balancing operational temperatures to minimise degradation while maintaining efficiency (Rochelle et al., 2012) [94]. Hong et al. (2020) [95] examined how different amines (MEA, DEA, MDEA, AMP) behave under various temperatures and provided insights into optimising amine regeneration at lower temperatures.

The changing climate increases the likelihood of droughts and hot weather, the impacts of this include water resources drought, reducing the amount of available water for abstraction for water supply. Global warming affects water sources by changing weather patterns (impacting annual rainfall), rising sea levels (causing flooding and operational disruptions) and decreasing water quality. The impacts of this on industry may reduce the available water supply to plants for process use.

3.2.5 Human Health Effects

The health and environmental impacts of carbon capture (CC) 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 adoption of these technologies increases in efforts to mitigate climate change. The HECC report [108] underlines that air pollution, significantly driven by fossil fuel combustion, is a leading environmental risk to public health in the UK, contributing to numerous deaths annually due to respiratory and cardiovascular diseases. It 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 such transitions for reducing greenhouse gas emissions and enhancing public health [96].

Zoback and Smit (2023) [97] in their study, explored the environmental and health impacts of large-scale CC 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 [98] [99] [48] [99], 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 [100]. The SCOPE project report (Lathouri et al., 2022) [101] delves into the health risks posed by nitrosamines and nitramines, emphasising their carcinogenic potential. It covers toxicological data, environmental guidelines, and the necessity of stringent safety measures to mitigate risks from these compounds. Special attention is given to sensitive populations like children, highlighting their increased vulnerability to these substances. The document advocates for the use of Quantitative Structure Activity Relationship (QSAR) models for hazard prediction and emphasises comprehensive monitoring and control measures to manage exposure via air, water, or occupational contact. Crucially, it provides specific numerical results for the Estimated Lifetime Cancer Risks (ELCRs) associated with exposure to NDMA, NDEA, and NPIP. For instance, the ELCR values for NDMA and NDEA underscore a significant risk, with the total ELCR for NDMA at 1.61×10^{-7} and for NDEA at 4.83×10^{-5}, indicating the substantial health risks involved. These findings underscore the importance of rigorous safety standards and continuous monitoring to protect public health around PCC facilities, particularly for vulnerable groups like children, who face a higher risk of cancer from exposure to these chemicals.

Chen et al. (2018) [102] in their comprehensive review, stated that the potential formation of nitrosamines and nitramines during amine degradation processes in CC technologies raises concerns due to their suspected carcinogenicity. These compounds may be emitted into the environment as by-products of the CO_2 capture process, posing risks to human health and ecosystems. The environmental and health impacts of these compounds are associated with high uncertainties, requiring further research to evaluate their significance and develop mitigation strategies.

3.2.6 Environmental Impacts

The hydrogenation of CO_2 not only aims at reducing CO_2 buildup but also produces fuels and chemicals, offering opportunities for sustainable development in energy and the environment. Despite the potential benefits, the environmental impacts associated with hydrogen production, especially from blue hydrogen (natural gas-based with carbon capture), may vary widely and depend on key parameters like the methane emission rate of the natural gas supply chain, the CO_2 removal rate at the production plant, and the warming metrics applied (Bauer et al., 2022) [28]. Furthermore, the production of green hydrogen, especially from low-carbon energy sources, has been linked to potential health benefits. A study conducted by Raouf (2023) [103] suggests that the production and use of green hydrogen not only contributes to environmental sustainability but also have 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) [103].

4.0 Review Limitations

The deliverables and scope of this project were limited by time and cost, therefore whilst every effort has been made to cover the key research questions, it is possible that additional information is available that has not been considered within this study. Only a comprehensive literature review could resolve this.

5.0 Challenges, Gaps and Future Research

The effective implementation and impact of CC technologies include several challenges that require a comprehensive and coordinated approach: Technological limitations are at the forefront of these challenges. Current CC systems, particularly amine-based ones, often struggle with efficiency in capturing and treating emissions. An integral part of addressing these challenges involves robust monitoring, both on-site to ensure the systems are functioning efficiently and ambient monitoring off-site to assess the environmental impact accurately and ensure compliance with environmental standards. Managing the degradation of amine solvents and the formation of harmful byproducts like nitrosamines and nitramines is a significant hurdle. Advancements in technology are required to overcome these limitations and enhance the effectiveness of CC systems.

Economic viability poses another major challenge. The high costs and energy-intensive nature of CC technologies, especially those involving amine-based processes, hinder their widespread adoption. Additionally, the introduction of these technologies often leads to new water demand, further complicating their implementation in water-scarce areas. Moreover, as new hydrogen production processes are integrated with carbon capture to create a more sustainable energy system, the economic considerations become even more complex, balancing the cost of innovative production methods against their environmental benefits. The energy penalty associated with CO_2 removal and increased capital and operating costs are key factors that need addressing to make these technologies more financially feasible. These challenges may hinder the development and implementation of CC, detracting from the potential financial benefits of innovative hydrogen and energy generation development in this area.

Environmental impacts of carbon capture (CC) technologies and nitrogen (N) deposition are significant concerns, particularly in ecosystems sensitive to nitrogen and acid deposition. A global assessment reveals nitrogen accumulation as a primary driver altering species composition across various ecosystems due to direct toxicity, soil acidification, and susceptibility to secondary stress factors (Bobbink et al., 2010) [104]. Despite decreases in nitrogen deposition, studies have observed limited responses in soil solution nitrate concentrations, understory vegetation, tree growth, or vitality, indicating that further reductions in nitrogen deposition alone might not lead to significant ecosystem recovery. This necessitates a broader approach considering accumulated nitrogen loads, climate change, and forest management (Schmitz et al., 2019 [105]; Dirnböck et al., 2018 [106]). The form of nitrogen deposition (reduced vs. oxidized) has been shown to differentially impact vegetation across habitat types, with acid and mesotrophic grasslands more sensitive to reduced nitrogen, and calcareous grasslands and woodlands more responsive to oxidised nitrogen, illustrating the complexity of nitrogen deposition impacts on biodiversity (Van den Van de Berg et al., 2016 [107]).

Challenges in mitigating the impacts of CC technologies and nitrogen deposition on ecosystems, particularly in protected habitats, include addressing the direct and indirect emissions from these systems and developing effective strategies to manage their broader ecological footprint. The complexity of ecosystem responses to nitrogen and acid deposition, the need for stringent emission reductions, and the implementation of comprehensive management strategies represent significant challenges in preserving biodiversity and ecosystem health.

Monitoring and compliance are integral to ensuring that CC technologies adhere to permitted emissions. Establishing robust monitoring systems and effective enforcement mechanisms is a complex task that involves both technical and regulatory aspects. The nature of the Tees Industrial Cluster increases the importance of stack monitoring and ambient air monitoring at sensitive human health and ecological receptors due to the potential number of CC technologies.

Finally, integrating CC technologies with existing industrial and power generation infrastructure presents its own set of technical and logistical challenges. Retrofitting old plants and ensuring compatibility with various operational settings are essential for the seamless adoption of these technologies.

Furthermore, the downstream utilisation of captured CO_2 underscores a pivotal challenge in ensuring that these efforts genuinely contribute to the reduction of total global emissions. The imperative to prevent the re-release of captured CO_2 into the atmosphere necessitates stringent regulatory oversight. This is particularly relevant in sectors like food and drink, as well as emerging Sustainable Aviation Fuel (SAF) production businesses, where the use of industrially captured CO_2, combined with green H_2 for manufacturing purposes, may lead to its subsequent re-emission. For instance, a proposed project aiming to utilise captured CO_2 alongside green H_2 for SAF production could inadvertently cycle CO_2 back into the atmosphere upon fuel use. Such scenarios highlight the critical need for regulations that not only promote the capture and utilisation of CO_2 but also ensure its permanent removal from the atmospheric cycle, thereby contributing to the overarching goal of reducing total global emissions.

Through cluster-scale mutual collaboration, several key challenges posed in hydrogen projects and carbon capture technologies can be addressed, besides taking the regulatory issues into consideration. For example, in the Tees area, current approaches to the funding of hydrogen projects, from source through distribution to the end-user, have led to plans for the construction of three separate hydrogen pipelines by three large H_2 projects. The consolidated approach, where a single H_2 distribution network serves as a BPEO, may rationalise infrastructure development and overcome space-induced challenges in some critical zones, e.g., river crossing tunnel pipelines. Further, such a partnership may stretch from mere sharing of infrastructure to collaborative programs for ambient air quality monitoring in ecological sites. This would give full-scale possibility toward new solvent emission degradation products and PCBs of EAF for comprehensive analysis, allowing their comprehensive indications of significance toward environmental concerns. Meanwhile, collaborative efforts on such a scale can optimally utilise resources with resourcefulness, improve the measures of environmental protection, and contribute to regional industrial capability development sustainably.

6.0 Conclusions and Recommendations

The review highlights significant concerns regarding the impact of air pollutants such as NO_x, PM_{10}, NH_3, SO_2 and amines on the region, emphasising the need for effective strategies to mitigate these effects. The transition towards hydrogen-based technologies and carbon capture utilisation and storage is recognised as a promising approach to reducing the carbon footprint of industrial activities. However, this transition must be managed with an acute awareness of the potential impacts on human health and sensitive ecological areas. These areas require particular attention to manage changes in nitrogen deposition, primarily due to increased NO_x generation from hydrogen combustion and ammonia/amine emissions from CC plant. The implementation of carbon capture technologies should be pursued with diligence to ensure that the ecological integrity of these regions is not compromised. Additionally, the recommendations call for a robust environmental monitoring framework. This framework should ensure that industrial activities comply with environmental regulations and standards to protect the region's ecological balance. The development of sustainable industrial practices is also emphasised, aiming to balance industrial growth with the preservation and improvement of the natural environment.

Overall, while CC and hydrogen generation technologies represent pathways toward reducing greenhouse gas emissions and transitioning to a low-carbon economy, their adoption must be navigated with awareness of the significant environmental and human health impacts they may entail. It is imperative to not only optimise these technologies to minimise direct emissions but also to ensure the environmental integrity of the entire process from the purity of captured CO_2 and produced hydrogen to a thorough assessment of their life cycle and the indirect effects on the atmosphere and ecosystems. This comprehensive approach is essential for ensuring that these technologies truly contribute to sustainability goals without adverse side effects.

These conclusions and recommendations denote the need for a coordinated approach that integrates environmental protection with industrial development, ensuring that low carbon technology deployment progresses sustainably and responsibly.

7.0 References

[1] A. C. D. M. J. *. K. S. Collins, “The Production of Quick Scoping Reviews and Rapid Evidence Assessments: A How to Guide. Science of the Environment,” Defra, 2015.

[2] T. e. al., “Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology.,” 2022.

[3] UK Health Security Agency (UKHSA), “Chapter 4: Impacts of climate change and policy on air pollution and human health.,” 2023. [Online]. Available: https://www.gov.uk/government/publications/climate-change-health-effects-in-the-uk.

[4] M. D. M. &. L. T. Dutka, “NOx emissions and turbulent flow field in a partially premixed bluff body burner with CH4 and H2 fuels.,” *International Journal of Hydrogen Energy, 41(28), ,* pp. 12397-12410, 2016.

[5] M. S. &. P. A. Cellek, “Investigations on performance and emission characteristics of an industrial low swirl burner while burning natural gas, methane, hydrogen-enriched natural gas and hydrogen as fuels,” *International Journal of Hydrogen Energy, 43(2),* pp. 1194-1207, 2018.

[6] Byworth Boiler, “OEM Consultation. s.l., s.n.,” Department for Energy Security and Net Zero (DESNZ), 2023.

[7] D. e. al., “NOx Emissions from Hydrogen-Methane Fuel Blends.,” 2022.

[8] M. L. &. L. A. C. Wright, “Emissions of NOx from blending of hydrogen and natural gas in space heating boilers.,” *Elementa: Science of the Anthropocene, 10(1). ,* 2022.

[9] S. &. B. A. Meziane, “Numerical study of blended fuel natural gas-hydrogen combustion in rich/quench/lean combustor of a micro gas turbine.,” *International Journal of Hydrogen Energy, 44(29).,* pp. 15610-15621, 2019.

[10] Environment Agency (EA), “Guidance on Emerging Technologies: Oxides of Nitrogen Emission limit values (ELVs) for combustion of hydrogen.,” 2024.

[11] A. C. Lewis, “Optimising air quality co-benefits in a hydrogen economy: a case for hydrogen-specific standards for NOx emissions.,” *Environmental Science: Atmospheres, 1(5).,* pp. 201-207, 2021.

[12] National Grid , “The hydrogen colour spectrum.,” 2023.

[13] K. B. D. Y. J. Z. H. M. V. &. L. E. Hein, “Optimal Operation of Green Hydrogen Generation Plant with Solar PV, Renewable Energy Certificates and Virtual Battery Ledger.,” in *IECON 2023- 49th Annual Conference of the IEEE Industrial Electronics Society. DOI: 10.1109/IECON51785.2023.10312380*, 2023.

[14] Q. A. I. S. S. H. M. O. O. &. J. M. Hassan, “Techno-Economic Assessment of Green Hydrogen Production by an Off-Grid Photovoltaic Energy System.,” Energies, 2023.

[15] B. &. A. Z. Yacine, “Integration of Renewable Energy in Green Hydrogen Generation.,” *International Journal of Advanced Natural Sciences and Engineering Researches,* 2023.

[16] G. U. K. H. J. S. P. D. K. W. B. B. L. Y. K. S. W. K. Y. B. M. J. J. S. &. L. U. Ingale, “Assessment of Greenhouse Gas Emissions from Hydrogen Production Processes: Turquoise Hydrogen vs. Steam Methane Reforming.,” Energies, 2022.

[17] J. H. J. K. D. &. W. Y. Holladay, “An overview of hydrogen production technologies.,” *Catalysis Today, 139.,* pp. 244-260, 2009.

[18] H. D. I. &. C. C. Ishaq, “A review on hydrogen production and utilization: Challenges and opportunities.,” *International Journal of Hydrogen Energy, 47(62).,* pp. 26238-26264, 2022.

[19] K. V. D. K. E. N. Á. E. J. H. J. &. F. D. C. Vilbergsson, “Can remote green hydrogen production play a key role in decarbonizing Europe in the future? A cradle-to-gate LCA of hydrogen production in Austria, Belgium, and Iceland.,” *International Journal of Hydrogen Energy, 48(46).,* pp. 17711-17728, 2023.

[20] C. Hristescu, “Analysis on the sustainability of different low CO2 emission Hydrogen production technologies for transition towards a ‘zero emission’ economy.,” 2022.

[21] I. G. T. A. B. M. A. K. A. A. A. M. &. H. A. H. Marouani, “Integration of Renewable-Energy-Based Green Hydrogen into the Energy Future.,” *Processes, 11(9). ,* 2023.

[22] D. P. F. C. W. D. R. S. M. &. B. O. Hauglustaine, “Climate benefit of a future hydrogen economy.,” *Communications Earth & Environment, 3(1). ,* 2022.

[23] J. Durling, “Best Available Techniques for ‘Blue’ Hydrogen Production with Carbon Capture and Storage.,” 2021.

[24] L. S. N. W. M. W. T. W. W. &. P. C. Zhang, “The integration of hydrogenation and carbon capture utilisation and storage technology: A potential low-carbon approach to chemical synthesis in China.,” *International Journal of Energy Research, 45.,* p. 19789 – 19818, 2021.

[25] A. O. A. K. G. T. D. L. G. &. K. A. Oni, “Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions.,” *Energy Conversion and Management, 254. ,* 2022.

[26] M. C. A. C. B. A. B. V. B. N. P. B. J. C. S. C. L. D. P. E. G. S. G. M. J. K. G. L. P. D. M. D. N. M. E. M. L. M. R. C. M. Romano, “Comment on “How green is blue hydrogen?",” *Energy Science & Engineering, 107,* pp. 1944-1954, 2022.

[27] R. W. &. J. M. Z. Howarth, “How green is blue hydrogen?,” *Energy Science & Engineering, 9(10).,* pp. 1676-1687, 2021.

[28] C. T. K. A. C. B. J. G. M. G. E. G. J. M. M. M. S. T. M. R. P. R. R. A. P. R. M. C. U. F. V. J. &. v. d. S. M. Bauer, “On the climate impacts of blue hydrogen production,” *Sustainable Energy & Fuels, Issue 6,* pp. 66-75, 2022.

[29] G. O. J. &. N. M. Wang, “Lifecycle impacts of natural gas to hydrogen pathways on urban air quality.,” *International Journal of Hydrogen Energy, 32(14).,* pp. 2731-2742, 2007.

[30] G. O. J. M. &. S. D. Wang, “Comparing air quality impacts of hydrogen and gasoline.,” *Transportation Research Part D: Transport and Environment, 13(7).,* pp. 436-448, 2008.

[31] W. e. al., “Atmospheric implications of increased Hydrogen use.,” 2022.

[32] I. B. &. H. S. P. Ocko, “Climate consequences of hydrogen emissions.,” *Atmospheric Chemistry and Physics, 22(14).,* pp. 9349-9368, 2022.

[33] B. L. J.-F. v. V. D. P. K. T. &. E. H. Van Ruijven, “Emission scenarios for a global hydrogen economy and the consequences for global air pollution.,” *Global Environmental Change, 21(3).,* pp. 983-994, 2011.

[34] Frazer-Nash Consultancy, “Fugitive Hydrogen Emissions Future Hydrogen Economy,” 2022.

[35] S. H. M. A. S. T. S. E. H. S. P. &. O. I. B. Esquivel-Elizondo, “Wide range in estimates of hydrogen emissions from infrastructure.,” *Frontiers in Energy Research, 11. ,* 2023.

[36] Q. e. a. Lai, “Hydrogen storage materials for mobile and stationary applications: Current state of the art.,” *ChemSusChem, 8(17).,* pp. 2789-2806, 2015.

[37] S. C. Singhal, “Advances in solid-oxide fuel cell technology.,” *Solid State Ionics, 357.,* pp. 115-130, 2000.

[38] T. e. a. Tromp, “Potential Environmental Impact of a Hydrogen Economy on the Stratosphere.,” *Science, 300(5626).,* pp. 1740-1742, 2003.

[39] A. Uguru, “An emission analysis study of hydrogen-powered vehicles.,” *International Journal of Hydrogen Energy, 45(48).,* pp. 26522-26535, 2020.

[40] K. &. H. J. Dillman, “Towards a Safe Hydrogen Economy: An Absolute Climate Sustainability Assessment of Hydrogen Production,” *Climate, 11(1),* 2023.

[41] S. e. al., “A multi-model assessment of the Global Warming Potential of hydrogen,” 2023.

[42] Environment Agency (EA), “Sector Guidance Note IPPC S2.01 Integrated Pollution Prevention and Control (IPPC) Guidance for the Production of Coke, Iron and Steel,” 2004.

[43] Intergovernmental Panel on Climate Change (IPCC), “Guidance for the Production of Coke, Iron and Steel, 2004.,” 2004. [Online]. Available: https://www.sepa.org.uk/media/60999/ippc-s201-guidance-for-the-coke-iron-and-steel-sector-issued-june-2004.pdf.

[44] J. e. a. Shen, “Polychlorinated Biphenyl Emissions from Steelmaking Electric Arc Furnaces.,” in *Bulletin of Environmental Contamination and Toxicology. DOI:10.1007/s00128-021-03105-x*, 2021.

[45] A. a. S. K. Rusin, “An Analysis of Hazards Caused by Emissions of Amines from Carbon Dioxide Capture Installations.,” 2016.

[46] F. e. al., “The impact of aromatic amines on the environment: risks and damages.,” 2012.

[47] G. e. al., “Assessment of the Impact of Various Amines on Micro- and Macro-organisms and their Potential Biodegradability in the Ecosystem.,” 2023.

[48] G. R. R. A. A. Y. Q. B. M. B. R. M. M. &. A. M. Puxty, “Carbon dioxide postcombustion capture: a novel screening study of the carbon dioxide absorption performance of 76 amines..,” *Environmental science & technology, 43 16, 6427-33.,* 2009.

[49] E. S. M. C. R. D. S. A. J. C. W. Sanz-Perez, “Direct Capture of CO2 from Ambient Air.,” *Chem. Rev. 116(19).,* p. 11840–11876, 2016.

[50] Scottish Environment Protection Agency (SEPA), “Review of amine emissions from carbon capture systems.,” 2022.

[51] Process Ecology , “Health and Environmental Impacts of Amine-based CO2 Capture Plant – A literature review.,” 2016.

[52] C. J. H. H. &. W. C. Nielsen, “Atmospheric chemistry and environmental impact of the use of amines in carbon capture and storage (CCS).,” *Chem Soc Rev, 41(19).,* pp. 6684-6704, 2012.

[53] T. C. T. K. A. T. A. W.-S. L. &. W. A. Spietz, “Ammonia emission from CO2 capture pilot plant using aminoethylethanolamine.,” *International Journal of Environmental Science and Technology, 15(5).,* pp. 1085-1092, 2017.

[54] NEA, “Carbon capture will halve emissions from Norcem Brevik.,” 2022.

[55] AECOM, “Net Zero Teesside – Environmental Statement,” 2017.

[56] K. e. al.., “Summary Report: Amine Emissions to Air during Carbon Capture.,” 2009.

[57] Environment Agency (EA), “Review of emerging techniques for hydrogen production from methane and refinery fuel gas with carbon capture.,” 2023.

[58] W. P. H. &. D. W. Wurtsbaugh, “Nutrients, eutrophication and harmful algal blooms along the freshwater to marine continuum.,” *Wiley Interdisciplinary Reviews: Water, 6. ,* 2019.

[59] A. D. e. a. Sha, “Application of ultraviolet, ozone, and advanced oxidation treatments to washwaters to destroy nitrosamines, nitramines, amines, and aldehydes formed during amine-based carbon capture.,” 2013.

[60] J. A. C. Z. K. A. Y. &. Y. S. Yin, “Handling of Amine-Based Wastewater Produced During Carbon Capture.,” *Journal of Environmental Informatics Letters. ,* 2019.

[61] A. K. N. B. P. S. C. M. F. J. K. T. R. B. U. Ø. U. H. Z. L. M. T. W. A. C. T. B. O. M. K. J. d. K. G. F.-P. O. &. H. E. S. Morken, “Emission Results of Amine Plant Operations from MEA Testing at the CO2 Technology Centre Mongstad,” *Energy Procedia, 63,,* pp. 6023-6038, 2014.

[62] V. Buvik, “Stability of amines for CO2 capture,” 2021.

[63] P. V. A. A. A. &. S. T. Pakchotanon, “Atmospheric Dispersion of Gaseous Amine Emitted from Absorption-Based Carbon Capture Plants in Saskatchewan, Canada.,” *Energies, 15(3). ,* 2022.

[64] E. e. al., “Review of Emissions from Post-Combustion Carbon Capture using Amine Based Technologies and Current Monitoring Techniques,” 2022.

[65] N. e. a. Flo, “Results from MEA Degradation and Reclaiming Processes at the CO2 Technology Centre Mongstad.,” Energy Procedia, 2017.

[66] P. R. H.-K. T. H. A. G. T. &. C. S. Gentry, “Potential occupational risk of amines in carbon capture for power,” *Health, 87(6).,* pp. 591-606, 2014.

[67] e. a. Brekke, “Environmental assessment of amine-based carbon capture: Scenario modelling with life cycle assessment (LCA),” 2012.

[68] J. e. al., “Machine learning for industrial processes: Forecasting amine emissions from a carbon capture plant.,” 2023. [Online]. Available: https://www.science.org/doi/10.1126/sciadv.adc9576.

[69] M. e. a. Azzi, “Emissions to the Atmosphere from Amine-Based Post Combustion CO2 Capture Plant - Regulatory Aspects,” 2014.

[70] European Commision (EC), “Best Available Techniques (BAT) reference document for large combustion plants – Industrial Emissions Directive 2010/75/EU integrated pollution prevention and control),,” European Commision (EC), 2017.

[71] M. e. al., “Development of Process Model of CESAR1 Solvent System and Validation.,” 2022.

[72] F. e. al., “Thermodynamic assessment of amine based CO2 capture technologies in power plants based on European Benchmarking Task Force methodology.,” 2014.

[73] G. S. F. E. R. S. M. E. G. E. L. V. &. V. T. J. H. Manzolini, “Economic assessment of novel amine based CO2 capture technologies integrated in power plants based on European Benchmarking Task Force methodology.,” *Applied Energy, 138.,* pp. 546-558, 2015.

[74] Greenhouse Gas Control Technologies 2016 (GHGT-16), “Results from CESAR1 testing at the CO2 Technology Centre Mongstad. Verification of Residual Fluid Catalytic Cracker (RFCC) baseline results.,” 2022.

[75] Greenhouse Gas Control Technologies 2016 (GHGT-16), “Air pollution impacts of amine scrubbing for CO2 capture.,” 2022.

[76] Badische Anilin- und Sodafabrik (BASF), “BASF and GS Engineering and Construction intend to jointly develop modular solutions for Carbon Capture,” 2022. [Online]. Available: https://www.basf.com/global/en/media/news-releases/2022/09/p-22-358.html.

[77] International CCS Knowledge Centre, “Standardized Testing Eliminates Amine-Based CCS Barriers,” 2020.

[78] Post Combustion Capture Conference 4 (PCCC4), “Résumé of the 10-year joint development program of BASF, Linde and RWE Generation at the post-combustion capture pilot plant at Niederaussem.,” 2017.

[79] Greenhouse Gas Control Technologies 2015 (GHGT-15), “Large Pilot Testing of Linde-BASF Advanced Post-Combustion Carbon Dioxide Capture Technology at a Coal-Fired Power Plant.,” 2021.

[80] J. &. D. D. W. Singh, “Overview of Carbon Capture Technology: Microalgal Biorefinery Concept and State-of-the-Art.,” *Frontiers in Marine Science, 6. ,* 2019.

[81] C. M. A. I. H. M. E. G. C. H. &. J. Z. I. Beal, “Integrating Algae with Bioenergy Carbon Capture and Storage (ABECCS) Increases Sustainability,” *Earth's Future, Issue 6,* pp. 524-542, 2018.

[82] D. D.-W. C. P. H. &. R. R. Tsai, “The potential of carbon dioxide capture and sequestration with algae.,” *Ecological Engineering, 98.,* pp. 17-23, 2017.

[83] I. v. d. S. R. &. G. E. Hernandez-Mireles, “New Methodologies for Integrating Algae with CO2 Capture.,” *Energy Procedia, 63.,* pp. 7954-7958 , 2014.

[84] T. I. P. &. P. D. Iglina, “Industrial CO2 Capture by Algae: A Review and Recent Advances.,” *Sustainability, 14(7). ,* 2022.

[85] P. J. &. P. M. Ralph, “Save the planet with green industries using algae.,” *PLoS Biol, 21(3), e3002061. ,* 2023.

[86] C-Capture, Ltd, “EA Q4 Emissions Report SB-CCL Trial.,” 2024. [Online]. Available: https://c-capture.co.uk/.

[87] F.-N. Consultancy., “Fugitive hydrogen emissions future hydrogen economy.,” 2022.

[88] G. e. al., “Leakage risk assessment of a CO2 storage site.,” 2021.

[89] M. S. R. B. S. M. K. S. M. G. B. H. D. R. H. D. P. F. P. M. &. S. D. Sand, “A multi-model assessment of the Global Warming Potential of hydrogen,” *Communications Earth & Environment, 4(1),* 2023.

[90] J. D. L. B. S. &. H. A. Cooper, “Hydrogen emissions from the hydrogen value chain-emissions profile and impact to global warming.,” *Sci Total Environ, 830, ,* p. 154624, 2022.

[91] K. F. A. &. M. S. T. An, “The impact of climate on solvent-based direct air capture systems,” *Applied Energy,* p. 352, 2022.

[92] F. R. A. &. O.-D. M. Petrakopoulou, “Impact of climate change on fossil fuel power-plant efficiency and water use.,” *Journal of Cleaner Production, 273. ,* 2020.

[93] European Commission (EC), “European Eel Regulation: Council Regulation (EC) No 1100/2007 of 18 September 2007 establishing measures for the recovery of the stock of European eel.,” 2007.

[94] G. T. Rochelle, “Thermal degradation of amines for CO2 capture.,” *Current Opinion in Chemical Engineering, 1(2).,* pp. 183-190, 2012.

[95] S. S. G. M. S. &. P. Y. Hong, “Low-Temperature Regeneration of Amines Integrated with Production of Structure-Controlled Calcium Carbonates for Combined CO2 Capture and Utilization.,” *Energy & Fuels, 34(3).,* pp. 3532-3539, 2020.

[96] UK Health Security Agency (UKHSA), “Chapter 14. Net zero: health impacts of policies to reduce greenhouse gas emissions.,” 2023. [Online]. Available: https://www.gov.uk/government/publications/climate-change-health-effects-in-the-uk.

[97] M. &. S. D. Zoback, “Meeting the challenges of large-scale carbon storage and hydrogen production.,” *Proceedings of the National Academy of Sciences of the United States of America, 120. ,* 2023.

[98] O.-A. e. al., “Effects of Composition, Structure of Amine, Pressure and Temperature on CO2 Capture Efficiency and Corrosion of Carbon Steels using Amine-Based Solvents: a Review.,” 2022.

[99] R. A. B. Rubin E. S., “A technical, economic, and environmental assessment of amine-based CO2 capture technology for power plant greenhouse gas control.,” 2002.

[100] S. e. al., “Nitrosamines and nitramines in Carbon Capture plants.,” 2017.

[101] e. a. Lathouri, “Human Health hazard assessment strategy for amine emissions around PCC facilities.,” 2022.

[102] X. H. G. A. C. Y. Y. &. Z. S. Chen, “Emerging N-nitrosamines and N-nitramines from Amine-based Post-combustion CO2 Capture - A Review,” *Chemical Engineering Journal, 335,* pp. 921-935, 2018.

[103] E. Raouf, “Green Hydrogen Production and Public Health Expenditure in Hydrogen-Exporting Countries.,” *International Journal of Energy Economics and Policy. ,* 2023.

[104] R. H. K. G. J. S. T. A. R. A. M. B. M. C. S. D. E. D. F. E. B. E. J. F. M. G. F. N. A. P. L. &. V. W. Bobbink, “Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis,” *Ecological applications: a publication of the Ecological Society of America, Issue 20 ,* pp. 30-59, 2010.

[105] A. S. T. B. A. B. F. D. T. J. J. P. J. P. M. P. A. S. J. V. A. &. V. W. Schmitz, “ Responses of forest ecosystems in Europe to decreasing nitrogen deposition..,” *Environmental pollution, 244, ,* pp. 980-994, 2019.

[106] T. e. a. Dirnböck, “Currently legislated decreases in nitrogen deposition will yield only limited plant species recovery in European forests.,” *Environ. Res. Lett. 13 ,* p. 125010, 2018.

[107] V. d. B. e. al., “Evidence for differential effects of reduced and oxidised nitrogen deposition on vegetation independent of nitrogen load,” 2016.

(108) Health efffects of Climate Change (HECC) in the UK: 2023

Table 2: Key Literature Review Research Points

Author	Date	Title	Key Points	Science Paper/ General Paper	Address	Category
Dillma & Heinonen	2023	Towards a Safe Hydrogen Economy: an Absolute Climate Sustainability Assessment of Hydrogen Production	Raised concerns about climate overshoot, with emissions potentially exceeding the safe space for greenhouse gases by 5.4–8.1 times by 2050. The cumulative carbon budget consumption of the hydrogen economy could be 8–12%.	Science Paper	https://doi.org/10.3390/cli11010025	Hydrogen Generation
Hein et al.	2023	Optimal Operation of Green Hydrogen Generation Plant with Solar PV, Renewable Energy Certificates and Virtual Battery Ledger	Green hydrogen is produced by the electrolysis of water, a process powered by electricity derived from renewable energy sources such as solar, wind, and wave power. This method involves splitting water into hydrogen and oxygen, without the need for combustion-based power, thus enabling the production of hydrogen without emitting CO_2.	Science Paper	DOI: 10.1109/IECON51785.2023.10312380	Hydrogen Generation
Yacine & Abderrahim	2023	Integration of Renewable Energy in Green Hydrogen Generation	Dark green hydrogen, a subset of green hydrogen, represents a commitment to maximum sustainability. It is produced through electrolysis powered directly and exclusively by renewable energy sources. Unlike other green hydrogen, which may use grid electricity that includes a mix of energy sources, dark green hydrogen ensures the electricity used for electrolysis comes solely from renewables not connected to the grid, minimizing the environmental footprint even further.	Science Paper	https://doi.org/10.59287/ijanser.579	Hydrogen Generation
Hassan et al.	2023	Techno-Economic Assessment of Green Hydrogen Production by an Off-Grid Photovoltaic Energy System	When electrolysis, the process used to produce hydrogen by splitting water into hydrogen and oxygen, is powered solely by solar energy, the resulting hydrogen is specifically referred to as "yellow hydrogen." This term highlights the use of a singular renewable energy source—solar power—in its production. The categorization into green, dark green, and yellow hydrogen emphasizes the differences in environmental impact and sustainability of the production processes. Among these, "dark green" hydrogen stands out as the ideal, signifying the use of renewable energy sources that are directly connected to the electrolysis process and not mixed with energy from the grid, thereby ensuring the highest level of sustainability and minimal environmental impact.	Science Paper	https://doi.org/10.1038/s43247-022-00626-z	Hydrogen Generation
National Grid	February 2023	The hydrogen colour spectrum	➢ Green Hydrogen: Made through clean electricity-driven water electrolysis from renewables. ➢ Blue Hydrogen: Derived from natural gas with carbon capture and storage. ➢ Grey Hydrogen: Produced from natural gas without carbon capture. ➢ Black and Brown Hydrogen: Environmentally damaging, often from coal. ➢ Pink Hydrogen: Generated via nuclear-powered electrolysis. ➢ Turquoise Hydrogen: Emerging low-emission hydrogen, produced through methane pyrolysis. ➢ Yellow Hydrogen: Produced through electrolysis using solar power. ➢ White Hydrogen: Naturally occurring hydrogen, not currently exploited.	General Article	The hydrogen colour spectrum| National Grid Group	Hydrogen Generation
Vilbergsson et al.	2023	Can remote green hydrogen production play a key role in decarbonizing Europe in the future? A cradle-to-gate LCA of hydrogen production in Austria, Belgium, and Iceland	The environmental sustainability of green hydrogen production is closely linked to the source of electricity used in the electrolysis process. This relationship becomes more complex when the production relies on intermittent sources of renewable energy, such as wind or solar power. The variable nature of these energy sources may necessitate adjustments in the operation schedules of electrolysis plants to ensure that the electricity used is indeed renewable and sustainable. The efficiency of the conversion process from electricity to hydrogen, the operating hours that align with the availability of renewable energy, and the potential need for electricity from the grid (which may include power generated from fossil fuels) are key factors that significantly influence both the efficiency and the environmental impact of green hydrogen production. These aspects underscore the importance of carefully planning and managing the electrolysis process to maximize the environmental benefits of green hydrogen.	Science Paper	https://doi.org/10.1016/j.ijhydene.2023.01.081	Hydrogen Generation
Hristescu	2023	Analysis on the sustainability of different low CO_2 emission Hydrogen production technologies for transition towards a ‘zero emission’ economy	The production of green hydrogen, characterized by its reliance on electrolysis powered by renewable energy sources, stands out for its high electricity demand. This demand is significantly greater than that for other low CO_2 hydrogen production methods, such as turquoise hydrogen, which is generated through methane pyrolysis, and conventional steam methane reforming (SMR) with CCS. Specifically, green hydrogen production requires more than triple the amount of green power compared to turquoise hydrogen and over 37 times that required for conventional SMR with CCS. This substantial energy requirement underscores the critical role of sustainable and economically viable energy sources in green hydrogen production. As such, the higher production costs associated with green hydrogen highlight the importance of integrating considerations of both sustainability and economic viability in the development and scaling of green hydrogen initiatives.	Science Paper	https://sciendo.com/article/10.2478/picbe-2022-0106	Hydrogen Generation

Author	Date	Title	Key Points	Science Paper/ General Paper	Address	Category
Marouani et al.	2023	Integration of Renewable-Energy-Based Green Hydrogen into the Energy Future	The European Union, China, the United States, Japan, Australia, and other countries have set ambitious targets for the production of green hydrogen, reflecting a global commitment to sustainable energy and carbon reduction. The European Union aims to produce 40 gigawatts (GW) of green hydrogen by 2030, leveraging policy support and advancements in renewable energy technologies. China has set a target of producing 5 million tonnes of green hydrogen annually by 2025, underscoring its focus on green energy transition. Similarly, the United States plans to achieve a production capacity of 5 GW of hydrogen by 2030, with projections suggesting a potential market size of up to USD 140 billion annually by 2050. These targets are part of a broader strategy to integrate green hydrogen into national energy systems, reduce carbon emissions, and foster economic growth within the emerging hydrogen economy. Japan and Australia, among other nations, also have significant ambitions for green hydrogen production, further demonstrating the global momentum towards embracing renewable energy sources and advancing hydrogen as a key component of the future energy landscape.	Science Paper	https://doi.org/10.3390/pr11092685	Hydrogen Generation
Esquivel-Elizondo et al.	2023	Wide range in estimates of hydrogen emissions from infrastructure	findings reveal a spectrum of emission rates associated with different hydrogen production methods, emphasizing the variability in environmental impacts across grey, blue, and green hydrogen production processes. The study delineates that grey hydrogen production, typically involving steam methane reforming, exhibits emission rates between 0.5% and 1.0%. In contrast, blue hydrogen, which also relies on steam methane reforming but incorporates CCS, shows a broader range of emission rates from 0.0% to 1.5%, suggesting a potential reduction in emissions due to the effectiveness of CCS technologies. Green hydrogen, produced through water electrolysis powered by renewable energy sources, is noted for having the widest range of emission rates, from 0.03% to 9.2%. This variability in green hydrogen's emission rates is attributed to the electrolysis process itself, which, despite being powered by renewable energy, can have higher associated emissions compared to traditional hydrogen production methods. These findings highlight the need for a nuanced understanding of the environmental impacts of hydrogen production, considering the specific methodologies and technologies employed.	Science Paper	https://doi.org/10.3389/fenrg.2023.1207208	Hydrogen Generation
Raouf	2023	Green Hydrogen Production and Public Health Expenditure in Hydrogen-Exporting Countries	Discusses the broader benefits of green hydrogen production beyond its direct environmental impact. The study posits that the shift towards green hydrogen as an energy source, known for its process of generating hydrogen through the electrolysis of water using renewable energy, effectively reduces CO_2 emissions. This reduction is pivotal in the global effort to mitigate climate change and its associated health risks. The analysis further suggests that countries investing in green hydrogen technology could see a positive impact on their public health systems. By decreasing reliance on fossil fuels and lowering CO_2 emissions, nations might be able to reallocate financial resources towards enhancing public health services and outcomes. This scenario underscores the intricate linkages between energy policy, environmental sustainability, and public health, indicating that decisions in one domain can have significant ripple effects across others. Raouf's insights highlight the potential of green hydrogen to contribute not just to a cleaner environment but also to healthier societies by enabling better public health investments.	Science Paper	https://doi.org/10.32479/ijeep.14484	Hydrogen Generation
I.B. Ocho and S. P. Hamburg	May 2022	Climate consequences of hydrogen emissions	1. Hydrogen's potential for warming the atmosphere is a major concern in an emerging hydrogen economy due to its pervasive leakage throughout the entire production and transportation process. 2. There is a lack of empirical data on hydrogen emissions because most measurements have focused on safety rather than climate impacts. 3. Uncertainty surrounds the future use and production of hydrogen and the technologies it might replace. 4. Hydrogen is expected to have a growing role in various sectors, and its leakage is a concern regardless of its production method. 5. Replacing fossil fuel technologies with hydrogen depends on the reduction of CO_2 and methane emissions. 6. The way hydrogen's warming effects are calculated and reported poses challenges and requires simplified metrics for better comparison with other greenhouse gases, typically using the Global Warming Potential (GWP) metric.	Science Paper	acp-22-9349-2022.pdf (copernicus.org)	Hydrogen Generation
Ishaq et al.	2022	A review on hydrogen production and utilization: Challenges and opportunities	The economic challenge of producing hydrogen, especially green hydrogen, is substantial. The traditional method of steam reforming, primarily used for producing hydrogen from natural gas, results in costs that are approximately three times higher per unit of energy produced when compared to the cost of natural gas itself. Similarly, producing green hydrogen through electrolysis, which involves splitting water into hydrogen and oxygen using electricity from renewable sources, incurs costs that can be double those of methods based on natural gas, with the exact figure heavily influenced by the price of electricity. This highlights the economic barriers to adopting green hydrogen as a more sustainable but currently more expensive alternative to fossil fuels.	Science Paper	https://doi.org/10.1016/j.ijhydene.2021.11.149	Hydrogen Generation

Author	Date	Title	Key Points	Science Paper/ General Paper	Address	Category
Sasan Saadat and Sara Gersen	August 2021	Reclaiming Hydrogen for a Renewable Future	1. The main focus is on "green hydrogen," produced using renewable electricity to power electrolysis, as the most sustainable form of hydrogen to combat climate change. 2. Industry claims of "clean," "renewable," or "green" hydrogen that include fossil-based hydrogen production methods, like steam methane reformation, are misleading and should be critically assessed. 3. Biomethane and biomass-derived hydrogen, despite industry labelling, may not provide significant climate benefits and can have public health and environmental drawbacks. 4. Hydrogen produced from fossil fuels with carbon capture (referred to as "blue hydrogen") is considered problematic, as it still involves emissions and significant costs while failing to address upstream methane leaks. 5. Policymakers should prioritize green hydrogen produced through renewable electrolysis and be cautious about the environmental and health implications of other hydrogen sources.	Science paper / Earthjustice website	https://earthjustice.org/wp-content/uploads/hydrogen_earthjustice_2021.pdf	Hydrogen Generation
Uguru et al.	2020	An emission analysis study of hydrogen-powered vehicles	This study presents a comparative analysis of CO_2 emissions from different types of vehicles, highlighting the significant environmental advantages of gaseous hydrogen-powered fuel cell vehicles over their liquid hydrogen-powered and traditional gasoline counterparts. Specifically, it was found that by 2050, gaseous hydrogen-powered fuel cell vehicles could achieve the lowest CO_2 emission values at 81 g/km. This represents a considerable reduction in emissions when compared to the 416 g/km observed for liquid hydrogen-powered spark ignition internal combustion engine vehicles in 2010. The findings underscore the potential of gaseous hydrogen fuel cell technology as a cleaner alternative for the automotive industry, offering a viable path towards reducing greenhouse gas emissions and advancing towards more sustainable transportation solutions.	Science Paper	https://www.sciencedirect.com/science/article/pii/S0360319920319583?via%3Dihub	Hydrogen Generation
Lai et al.	2015	Hydrogen storage materials for mobile and stationary applications: Current state of the art	Bulk Hydrogen Storage: Ammonia is recognized as an efficient hydrogen carrier due to its high hydrogen density, facilitating bulk storage. The theoretical hydrogen conversion efficiency from ammonia is about 90%, making it advantageous for large-scale storage and transportation.	Science Paper	https://chemistry-europe.onlinelibrary.wiley.com/doi/abs/10.1002/cssc.201500231	Hydrogen Generation
Ruijven et al.	2011	Emission scenarios for a global hydrogen economy and the consequences for global air pollution	The study offers a comprehensive analysis of hydrogen leakage rates across various stages of the hydrogen supply chain, including transport, distribution, and end-use. Their study highlights the complexities involved in managing hydrogen's small molecular structure, which can lead to significant leakage rates and energy losses, especially during long-distance transportation. For instance, the study points out that a sea journey of 2,400 km for transporting hydrogen could result in energy losses of about 4.8%, accompanied by atmospheric emissions of 2-3%. This detailed examination underscores the logistical challenges and environmental considerations that must be addressed to optimize the hydrogen supply chain for safety, efficiency, and minimal environmental impact.	Science Paper	https://doi.org/10.1016/j.gloenvcha.2011.03.013	Hydrogen Generation
Guihua Wang et al.	January 2007	Lifecycle impacts of natural gas to hydrogen pathways on urban air quality	1. All hydrogen pathways result in minimal air pollution, less than 0.1% of current ambient pollution levels. 2. Central steam methane reformer (SMR) with pipeline delivery is the cleanest option, followed by onsite hydrogen production. 3. Liquid hydrogen trucks have a greater impact due to emissions from diesel trucks and electricity use for hydrogen liquefaction. 4. Emissions from hydrogen plant operations are less significant compared to other pollution sources.	Science paper	Lifecycle impacts of natural gas to hydrogen pathways on urban air quality - ScienceDirect	Hydrogen Generation

Author	Date	Title	Key Points	Science Paper/ General Paper	Address	Category
R. Derwent et al.	2006	Global environmental impacts of the hydrogen economy	***Hydrogen as an Energy Source:*** Hydrogen-based energy systems are considered a promising replacement for current fossil-fuel-based systems. While hydrogen is a minor component of the atmosphere, it has significant man-made and natural sources. A future hydrogen economy could potentially reduce reliance on fossil fuels but would not be entirely free from climate perturbations. ***Hydrogen in the Atmosphere:*** The average global mixing ratio of hydrogen is around 510 ppb, with variations between the northern and southern hemispheres. Despite human influences, hydrogen levels have remained relatively constant over the past decades, with minor fluctuations observed. ***Global Hydrogen Budget:*** Hydrogen production is primarily from human activities, including fossil fuel combustion (especially from petrol-engined vehicles) and biomass burning. Hydrogen is also a by-product of nitrogen fixation in plants and is generated from the oxidation of methane and other organic compounds by hydroxyl radicals. The main sink for atmospheric hydrogen is its uptake by soils, which accounts for a significant portion of hydrogen removal from the atmosphere. ***Hydrogen as an Indirect Greenhouse Gas:*** Hydrogen can influence the distribution of methane and ozone, the second and third most important greenhouse gases after CO_2. Therefore, it is classified as an indirect greenhouse gas. Emissions of hydrogen and other ozone precursors can alter the distribution of hydroxyl radicals in the troposphere, which in turn affects the global buildup of methane. ***Greenhouse Gas Consequences of a Global Hydrogen Economy:*** The transition to a hydrogen economy has implications for global warming. If the global hydrogen production capacity were to replace the entire current fossil-fuel-based energy system, and assuming a leakage rate of 1%, the hydrogen economy would emit about 25 Tg H_2 per year. This would result in a climate impact of 0.6% compared to the current fossil fuel system. However, if the leakage rate were higher, at 10%, the climate impact would be 6% of the current system. Therefore, minimizing hydrogen leakage during synthesis, storage, and utilization is crucial to realize its full climate benefits compared to fossil fuels.	Science paper	Global environmental impacts of the hydrogen economy | Advanced Global Atmospheric Gases Experiment (mit.edu)	Hydrogen Generation
Tromp et al.	2003	Potential Environmental Impact of a Hydrogen Economy on the Stratosphere	The deployment of hydrogen fuel cells, while heralded for their environmental benefits in reducing greenhouse gas emissions, carries potential atmospheric implications. A notable environmental concern is the unintended emission of molecular hydrogen, which has the capacity to augment the concentration of water vapor in the stratosphere by an estimated 1 part per million by volume. This increment in stratospheric water vapor could induce a series of atmospheric changes with broad implications. These include stratospheric cooling, which could alter global climate patterns; enhancement of the heterogeneous chemistry responsible for ozone depletion, thereby affecting the ozone layer's protective function; an increase in noctilucent clouds, which are high-altitude clouds that could have unknown climatic effects; and alterations in tropospheric chemistry and atmosphere-biosphere interactions, potentially impacting air quality and ecosystem health. These findings highlight the need for careful consideration of the broader environmental impacts of adopting hydrogen fuel cell technology, underscoring the importance of managing hydrogen emissions to mitigate these potential atmospheric consequences.	Science Paper	https://www.science.org/doi/10.1126/science.1085169	Hydrogen Generation
Singhal S.C.	2000	Advances in solid-oxide fuel cell technology.	Ammonia Cracking at Fuel Stations: Solid-oxide fuel cells can effectively convert ammonia back to electricity, showcasing ammonia's potential as a sustainable fuel, especially for on-site hydrogen production at fuel stations	Science Paper	https://www.sciencedirect.com/science/article/pii/S0167273800004525	Hydrogen Generation
Sand et al.	2023	A multi-model assessment of the Global Warming Potential of hydrogen	100-year Global Warming Potential (GWP100) of hydrogen to be 11.6 ± 2.8. Hydrogen affects the climate due to its indirect impacts on gases like methane, ozone, and stratospheric water vapour. The major contributors to its GWP100 are changes in methane, ozone, and stratospheric water vapour.	Science Paper	https://doi.org/10.1038/s43247-023-00857-8	Hydrogen Generation / Hydrogen Use
Leigh Collins	March 2022	Hydrogen blending will raise consumer costs and risk public health while barely reducing emissions: US think-tank	A 30% hydrogen blend — which the report says is representative of current utility proposals — would only reduce CO_2 emissions by 12%. “Perhaps most importantly, hydrogen’s higher flame temperature means a 50-50 blend with natural gas would drive 35% higher NO_x emissions relative to burning 100% natural gas,” the report explains. “Compliance with existing or future regulations may require that project owners install larger or more efficient NO_x control (selective catalytic reduction) systems or reduce assets’ flame temperature (which also reduces their power output and, in turn, their heat efficiency and competitiveness). While turbine manufacturers are exploring new technologies to limit NO_x emissions from burning hydrogen, they have yet to find viable solutions.” The third reason is that hydrogen-fired gas turbines are not yet commercially available and that existing turbines can only work with H_2 blends of up to 30%.	General article	Hydrogen blending will raise consumer costs and risk public health while barely reducing emissions: US think-tank | Recharge (rechargenews.com)	Hydrogen Generation / Hydrogen Use
Hauglustaine et al.	2022	Climate benefit of a future hydrogen economy	The environmental impact of hydrogen production varies significantly across different pathways, with green hydrogen presenting a positive effect by significantly reducing CO_2 emissions, in contrast to blue hydrogen, which may impose a climate penalty if associated with high leakage rates. Effective management of hydrogen leakage throughout the entire production, transport, storage, and use phases is critical for minimizing its climate impact. While a green hydrogen economy holds the promise of substantial CO_2 abatement, the benefits could be compromised in scenarios where blue hydrogen is involved, especially when leakage rates are not adequately controlled. This emphasizes the necessity of meticulous planning and implementation strategies for a hydrogen-based energy economy to ensure its environmental benefits are fully realized and potential adverse impacts are mitigated.	General article	https://doi.org/10.1038/s43247-022-00626-z	Hydrogen Generation / Hydrogen Use

Author	Date	Title	Key Points	Science Paper/ General Paper	Address	Category
Hevin Topolski et al.	October 2022	Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology	Many blending demonstrations internationally have proven that low-hydrogen-percentage blending is feasible under very specific scenarios with limited end-usage applications on both high-pressure transmission lines and low-pressure distribution lines. Many projects under commission are targeting higher blends of hydrogen, some up to 100%. The United States has successfully commissioned a handful of blending projects, but to date, the most successful and longest-running one is Hawaii Gas's introduction of a 12% to 15% blend in its network. Despite these successes, additional research across the entire hydrogen and natural gas supply chain will be needed to fill current knowledge gaps and better inform decision-makers on future blending projects.	Technical Report	nrel.gov/docs/fy23osti/81704.pdf	Hydrogen Generation / Hydrogen Use
Romano et al.	2022	Comment on “How green is blue hydrogen?	The critique of Howarth and Jacobson's study points out that their estimates of methane leakage rates are higher than those observed in many countries, suggesting that lower rates are achievable through the application of existing technologies at minimal costs. This observation is crucial for the role of blue hydrogen in transitioning to a decarbonised economy. For blue hydrogen to be considered a viable component of such a transition, it must demonstrate significantly lower greenhouse gas emissions compared to the direct use of fossil fuels like natural gas. This necessitates a concerted effort to minimize methane leakage throughout the production process, thereby reducing the overall greenhouse gas emissions associated with blue hydrogen.	Paper response	https://doi.org/10.1002/ese3.1126	Hydrogen Generation / Hydrogen Use
Ocko & Hamburg	2022	Climate consequences of hydrogen emissions	The importance of this research lies in its focus on the broader climate implications of hydrogen use, beyond the direct emissions associated with its production and consumption. It suggests that the environmental benefits of hydrogen as an energy carrier can be compromised by its indirect effects on climate, particularly if leakage rates are not adequately controlled. Ocko and Hamburg emphasize the need for comprehensive climate change mitigation strategies that account for all potential sources of greenhouse gas emissions, including those that are indirect and less obvious. Their findings underscore the importance of developing and implementing robust systems for hydrogen production, storage, and distribution that minimize leakage, thereby ensuring that hydrogen can fulfil its potential as a key component of a sustainable, low-carbon energy future.	Science paper	https://doi.org/10.5194/acp-22-9349-2022	Hydrogen Generation / Hydrogen Use
Clean Energy Group	September 2021	Five Reasons to Be Concerned About Green Hydrogen	Concerns about Hydrogen in the Power Sector: NO_x emissions – Diversion of renewable energy – Public health – High water usage – Storage and Transport – Dangers of Explosion	General Paper	https://www.cleanegroup.org/wp-content/uploads/Five-Reasons-to-be-Concerned-About-Green-Hydrogen.pdf	Hydrogen Generation / Hydrogen Use
Howarth & Jacobson	2021	How green is blue hydrogen?	The impact of fugitive methane emissions is crucial in evaluating the overall greenhouse gas (GHG) footprint of blue hydrogen production. When accounting for methane leakage, the GHG footprint of blue hydrogen exceeds that of directly utilizing natural gas or coal for heating by more than 20%. This highlights the significant environmental considerations associated with methane emissions in the process of producing blue hydrogen, underscoring the need for effective measures to manage and minimize methane leakage to ensure the environmental viability of blue hydrogen as a lower-carbon energy source.	Science Paper	https://doi.org/10.1002/ese3.956	Hydrogen Generation / Hydrogen Use
Guihua Wang et al.	October 2008	Comparing air quality impacts of hydrogen and gasoline	***Hydrogen Supply Pathways:*** Three natural gas-based hydrogen supply pathways were analysed: a. Onsite hydrogen production via small-scale steam methane reforming (SMR). b. Central large-scale hydrogen production via SMR with gaseous hydrogen pipeline delivery. c. Central hydrogen production via SMR with liquid hydrogen truck delivery. ***Lifecycle Emission Inventories:*** Lifecycle emissions include all emissions involved in producing and delivering hydrogen to vehicles as well as emissions from electricity generation (for hydrogen compression or liquefaction) and diesel fuel combustion (in hydrogen delivery trucks). ***Air Quality Impacts:*** The centralized/pipeline hydrogen pathway reduces pollution the most, followed by onsite hydrogen production, and the centralized hydrogen production with liquid hydrogen truck delivery. Gasoline pathways, even with advanced new vehicles, would lead to much higher ambient concentrations of pollutants than any of the hydrogen pathways. ***Comparison Between Hydrogen and Gasoline Pathways:*** Gasoline pathways with current technologies would lead to 510 times greater CO, 150 times greater VOC, 10 times greater PM_{10}, and 10 times greater NO_x concentrations than those caused by the centralized/pipeline hydrogen pathway. Gasoline pathways with advanced technologies (year 2025 vehicles) would still lead to significantly higher concentrations of pollutants than any of the hydrogen pathways. ***Implications:*** Introducing hydrogen pathways analysed would improve urban air quality compared to the 2005 on-road scenario in the following order: CO > VOC > NO_x > PM_{10}.	Science Direct	https://www.sciencedirect.com/science/article/abs/pii/S1361920908001028	Hydrogen Generation / Hydrogen Use

Author	Date	Title	Key Points	Science Paper/ General Paper	Address	Category
Nicola Warwick et al.	April 2022	Atmospheric implications of increased Hydrogen use	The study focuses on emission reductions in methane (CH_4), carbon monoxide (CO), NO_x, and volatile organic compounds (VOCs). 1. Emission reductions in an illustrative hydrogen economy scenario (where 23% of global final energy consumption is supplied by hydrogen) are determined by applying a uniform global scaling factor to emissions in specific energy sectors where hydrogen plays a role. 2. The majority of CH_4 emissions in the UK come from downstream leaks rather than during production, suggesting that switching to SMR-based H2 might not significantly affect global CH_4 emissions if downstream leaks are eliminated. 3. Other low-carbon hydrogen production methods, such as electrolysis or biomass gasification, are being proposed to avoid CH_4 and CO_2 emissions associated with SMR. 4. H2 leakage rates are likely to be higher than for natural gas owing to the small molecule size of H_2. A recent study looking at the US natural gas supply chain indicated natural gas leaks of around 2.3% of gross gas.	Gov Paper	Atmospheric implications of increased hydrogen use (publishing.service.gov.uk)	Hydrogen Use
Schroder et al.	2022	Experimental mild conversion of a lean burn natural gas engine with SCR to a hydrogen engine: NO_x and GWP potential for marine applications	Pre-SCR (Selective Catalytic Reduction) NOx emissions of pure hydrogen are comparable to natural gas in marine engines, highlighting the importance of after-treatment systems.	Science Direct	https://doi.org/10.1177/14680874221121032	Hydrogen Use
Douglas et al.	2022	Pollutant Emissions Reporting and Performance Considerations for Hydrogen–Hydrocarbon Fuels in Gas Turbines	The study highlights that volume-based measurements show higher NOx emissions for systems using hydrogen or hydrogen blends, requiring a 36 to 40% correction. This increase is due to the larger volumes of H2O and O_2 in the combustion products of hydrogen systems, which, despite having the same mass production rate of NOx as methane, report higher emissions when measured in volume-based metrics (ppmv @ 15% O_2).	Science Paper	https://doi.org/10.1115/1.4054949	Hydrogen Use
Wright & Lewis	2022	Emissions of NO_x from blending of hydrogen and natural gas in space heating boilers	The study conducted a detailed meta-analysis on NOx emissions from burning hydrogen and natural gas blends in boilers, focusing on up to 20% hydrogen by volume—a key part of the UK's strategy for hydrogen integration. It found significant variability in NOx emissions when hydrogen is added to natural gas, with emissions for a 5% hydrogen blend fluctuating between a 12% decrease and a 39% increase compared to natural gas alone. For a 20% hydrogen blend, the variation was even broader, with potential decreases of 50% in NOx emissions or increases up to 154%, highlighting the complex impact of hydrogen blending on NOx emission levels.	Science Paper	https://doi.org/10.1525/elementa.2021.00114	Hydrogen Use
Alastair C. Lewis	June 2021	Optimising air quality co-benefits in a hydrogen economy: a case for hydrogen specific standards for NO_x emissions	1. Hydrogen as a net-zero fuel is promising but faces environmental challenges in production, distribution, and usage. 2. Hydrogen combustion may be adopted in many industries, and while it won't worsen NO_x emissions, it might not improve them either. 3. Hydrogen combustion could have benefits in terms of carbon monoxide and particulate matter emissions, but it might need new emission standards to reduce NO_x emissions. 4. Transitioning to hydrogen for backup power generation could lead to unintended air quality issues if not managed well. 5. It's technically feasible to achieve low NO_x emissions from hydrogen combustion, but it might require innovation and regulatory measures. 6. Complex regulatory responsibilities for hydrogen end-use may span different government departments, and setting new standards is crucial before widespread hydrogen adoption. 7. Prioritizing alternatives like home insulation and heat pumps could be a more economically balanced approach if NO_x emissions are minimized. 8. Acting before substantial hydrogen investments are made is essential for effective regulation.	Science paper	Optimising air quality co-benefits in a hydrogen economy: a case for hydrogen-specific standards for NO x emissions - Environmental Science: Atmospheres (RSC Publishing) DOI:10.1039/D1EA00037C	Hydrogen Use
Meziane & Bentebbiche	2019	Numerical study of blended fuel natural gas-hydrogen combustion in rich/quench/lean combustor of a micro gas turbine	Conducted a numerical analysis to evaluate NO_x emissions from fuel mixtures of natural gas and hydrogen. Their study compared experimental data with outcomes from two distinct numerical simulation methods. The findings indicated that adding a modest amount of hydrogen—just 10%—to natural gas could lead to a significant reduction in emissions: NO_2 emissions dropped by 14%, and CO_2 emissions decreased by 60%. This research underscores the potential environmental benefits of incorporating hydrogen into natural gas for combustion processes.	Science paper	https://doi.org/10.1016/j.ijhydene.2019.04.128	Hydrogen Use
Cellek and Pinarbasi	January 2018	Investigations on performance and emission characteristics of an industrial low swirl burner while burning natural gas, methane, hydrogen-enriched natural gas and hydrogen as fuels	Focused on the performance and emission characteristics of an industrial low swirl burner while burning natural gas, methane, and hydrogen-enriched fuels. Specifically, the study utilized a burner supplied by Termo-Heat Isı San. A.S, which was designed to operate under a constant burner load of 1085 kW and various cooling conditions in the boiler.	Science Direct	https://www.sciencedirect.com/science/article/abs/pii/S0360319917319791?via%3Dihub	Hydrogen Use
Dutka et al.	2016	NO_x emissions and turbulent flow field in a partially premixed bluff body burner with CH4 and H2 fuels. International Journal of Hydrogen Energy, 41(28), 12397-12410	The study examined NOx emissions from burners operating at thermal loads between 10 and 25 kW and temperatures from 1050°C to 1350°C. The lowest NO_x emissions, recorded at a 10 kW power load, were 55 mg/kWh for methane and 102 mg/kWh for hydrogen, measured at a dry basis of 3% O_2.	Science Direct	https://doi.org/10.1016/j.ijhydene.2016.05.154	Hydrogen Use

Author	Date	Title	Key Points	Science Paper/ General Paper	Address	Category
Environment Agency	January 2023	Review of emerging techniques for hydrogen production from methane and refinery fuel gas with carbon capture	***CO_2 Capture:*** ➢ CO_2 capture from the hydrogen product stream is typically achieved through absorption in a circulating chemical solvent with subsequent regeneration. ➢ Optimizing solvent selection and parameters is crucial to maximize energy efficiency and capture performance. ➢ Various factors must be considered, including lean solvent conditions, regeneration pressure, heat exchange for solvent regeneration, and recovery of CO_2 at higher pressure. ➢ Technology to reduce heat requirements for solvent regeneration, such as semi-lean solvent streams, should be considered. ➢ Absorber design should minimize solvent carry-over to downstream processes, minimizing its impact. ***Post-Combustion CO_2 Capture:*** ➢ Post-combustion capture can achieve high CO_2 capture rates of 95% or greater. ➢ Design of post-combustion CO_2 capture systems should consider variations in flue gas flow and conditions, as well as the reaction of amine solvent with NO_x, and the potential need for upstream NO_x removal. ***Emissions Monitoring:*** ➢ Emissions monitoring for pollutants such as ammonia, amine compounds, SO_2, NO_x, carbon monoxide, and methane should be carried out based on the expected emissions. ➢ Where post-combustion CO_2 capture is employed, emissions monitoring should also consider substances like ammonia, volatile components of the solvent, and degradation products. ➢ Monitoring standards for discharges to water should follow established BAT conclusions for waste gas and wastewater treatment in the chemical sector. ***Hydrogen Purification:*** ➢ Hydrogen purification is essential to meet the specified hydrogen product quality and remove impurities. ➢ Impurities that need to be addressed include nitrogen, methane, carbon monoxide, CO_2, and water. ➢ Depending on the product gas specification, methanation (conversion of CO to methane) can be considered as an alternative to impurity separation. ➢ Start-up and shut-down procedures for methanation reactors should be implemented to prevent the formation of toxic nickel carbonyl from the reaction of CO with the nickel catalyst. ***Off-Gas Production:*** ➢ Off-gas produced from hydrogen purification is typically rich in hydrogen and used as a fuel within the process. ➢ The slip of methane or carbon monoxide in the off gas should be optimized to meet CO_2 capture objectives while considering environmental impacts and energy use. ➢ In POX-based hydrogen production, off-gas use as fuel may not be required, and alternative uses or adaptations to the facility should be considered. ***Emissions to Air and Water:*** ➢ Monitoring of emissions to air and water should be based on expected pollutants or impurities, with suitable methods and techniques employed. ➢ Specific monitoring standards and thresholds should follow relevant BAT conclusions and regulations for individual pollutants.	Report	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1127275/Review_of_emerging_techniques_for_hydrogen_production_from_methane_and_refinery_fuel_gas_with_carbon_capture.pdf	Carbon Capture - Amine-Based Technologies / Hydrogen Generation
Zoback & Smit	2023	Meeting the challenges of large-scale carbon storage and hydrogen production	Investigated the environmental and health implications of large-scale carbon capture (CC) and hydrogen production projects. Their research advocates for prioritizing areas with existing, partially depleted oil and gas reservoirs for CO_2 storage, arguing that this strategy is not only safer but also more economically feasible for massively scaling up carbon sequestration efforts. By integrating large-scale hydrogen production, this approach aims to significantly cut down greenhouse gas emissions. The study underscores the importance of comprehensively understanding and addressing any potential health risks associated with such expansive operations. This is deemed essential to protect the well-being of populations residing in or near oil- and gas-producing regions, ensuring that the push towards reducing carbon footprints and transitioning to cleaner energy sources does not come at the cost of public health.	Science Paper		Carbon Capture / Hydrogen Generation
Bauer et al.	2022	On the climate impacts of blue hydrogen production	Focusing on two distinct configurations, "CCS-low" and "CCS-high," both utilizing MDEA as the solvent for CO_2 capture, the study presents a nuanced view of the potential efficiencies in CO_2 capture processes associated with hydrogen production. The "CCS-low" configuration is associated with a Steam Methane Reforming (SMR) process, augmented by a high-temperature water-gas shift reaction to enhance the hydrogen yield. This configuration achieves a CO_2 capture rate of 55%, with an impressive 90% capture rate from the syngas, indicative of a substantial reduction in CO_2 emissions albeit not maximizing the potential for CO_2 capture. Conversely, the "CCS-high" configuration is tied to an Autothermal Reforming (ATR) process, which combines the reforming and partial oxidation of methane in a single step, facilitating a more integrated approach to CO_2 capture. This process manages to capture up to 98% of CO_2 from the syngas, culminating in a plant-wide capture rate of 93%. This higher rate of capture underscores the potential of ATR processes, coupled with effective carbon capture configurations, to significantly mitigate CO_2 emissions in hydrogen production, aligning with stringent environmental goals.	Science Paper	https://doi.org/10.1039/d1se01508g	Carbon Capture / Hydrogen Generation

Author	Date	Title	Key Points	Science Paper/ General Paper	Address	Category
Zhang et al.	2021	The integration of hydrogenation and carbon capture utilisation and storage technology: A potential low-carbon approach to chemical synthesis in China	The integration of CCS within the hydrogen industry is emphasized as a crucial strategy for accelerating carbon emission reductions by 2050. This approach is highlighted from technical, sustainability, and policy perspectives, underscoring the importance of reviewing and assessing the feasibility of existing Carbon Capture, Utilization, and Storage (CCUS) alongside hydrogen production technologies. The discussion aims to explore how the incorporation of CCUS into the hydrogen sector can significantly contribute to achieving broader climate goals, by offering a pathway to reduce CO_2 emissions effectively within this rapidly evolving energy sector.	Science Paper	https://doi.org/10.1002/er.7076.	Carbon Capture / Hydrogen Generation
Tom Glyn-Jones et al.	July 2021	The Environmental Constrains of Net-Zero	The report acknowledges the potential opportunities and challenges associated with Hydrogen and CCUS technologies, which are seen as crucial by the UK government and Climate Change Committee in achieving Net Zero emissions by 2050. To succeed, the report underscores the importance of addressing these technologies' benefits and risks promptly and transparently. This will instil confidence among investors, regulators, and the public, ensuring that these technologies can operate effectively within environmental constraints and prioritize human health while facilitating a smooth transition towards a Net-Zero future.	Energy Research Partnership	https://erpuk.org/project/the-environmental-constrains-of-net-zero/ (not available)	Carbon Capture / Hydrogen Generation
HM Government	March 2021	Industrial Decarbonisation Strategy	The CCUS option is the predominant technology solution to abate process emissions in clusters (~ 6 $MtCO_2$ including BECCS). BECCS is used in situations that allow for combustion of biomass in place of traditional fossil fuels in glass, lime, cement and paper industries. BECCS is chosen instead of CCUS alone because improvement in carbon cost-effectiveness arises from negative emissions. Hydrogen (~ 20TWh) is favoured over electrification for processes requiring heat which is typical in food and drink, automotive, chemicals, and paper industries.	Gov paper	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/970229/Industrial_Decarbonisation_Strategy_March_2021.pdf	Carbon Capture / Hydrogen Use
EPA	February 2023	Anticipating the Environmental Impacts and Behavioural Drivers of Deep Decarbonization	US commitment to limit global average temperature rise under the United Nations Framework Convention on Climate Change (UNFCCC). It emphasizes the need for significant reductions in greenhouse gas (GHG) emissions to achieve this goal and outlines the U.S. targets for emissions reductions. The text briefly mentions the use of fossil fuels with CCS and notes that it may have potentially serious negative environmental impacts that could be challenging to mitigate to current environmental protection standards.	EPA website	https://www.epa.gov/research-grants/anticipating-environmental-impacts-and-behavioral-drivers-deep-decarbonization	Carbon Capture
A. N. Ullman and N. Kittner	April 2022	Environmental impacts associated with hydrogen production in La Guajira, Colombia	1. Coal mining communities like La Guajira may consider using coal for liquid hydrogen (LH2) production, but it raises environmental concerns. 2. Coal electrolysis is the least efficient LH2 production method, emitting significant CO2 and methane. 3. Coal-based LH2 scenarios lead to air pollution issues (SO_2, NO_x, PM) affecting ecosystems, agriculture, and respiratory health. 4. High levels of arsenic, lead, and mercury emissions from coal scenarios pose health risks (respiratory, nervous systems, kidney). 5. Coal-based LH2 production consumes significant water, a concern in regions vulnerable to climate change-induced drought. 6. Wind-fuelled LH2 scenarios have the lowest environmental impact. 7. Future hydrogen strategies should consider comprehensive impacts and just transition for affected communities.	Science paper	Environmental impacts associated with hydrogen production in La Guajira, Colombia (iop.org)	Carbon Capture
A.G. Olabi et al.	August 2022	Large scale application of carbon capture to process industries – A review	➢ *CC Energy Demand*: Carbon capture increases energy use, prompting the need for a metric like 'carbon emissions avoided' to truly assess its effectiveness. ➢ *Cost Variability*: Costs of CC are highly variable and industry-specific, often requiring subsidies or tax incentives to be feasible. ➢ *Need for Innovation*: Research and development are crucial in creating more energy and material-efficient CC technologies. ➢ *Policy Influence*: Tax credits and subsidies significantly affect the economic viability of CC projects. ➢ *Renewable Energy for CC*: Integrating renewables like solar or wind can make CC processes CO_2-neutral. *Industry-Specific CC Applications*: Applying CC to industries like cement and steel shows promise for substantial emissions reductions.	Science Paper	https://www.sciencedirect.com/science/article/abs/pii/S0959652622019047	Carbon Capture
An et al.	2022	The impact of climate on solvent-based direct air capture systems	An et al. (2022) discovered that CO_2 capture rates can reach up to 85% in hot and humid climates, but significantly decrease in cooler and drier conditions. For example, achieving a CO_2 capture rate of 75% requires conditions of at least 17°C and 90% relative humidity. This finding underscores the influence of climate on the efficiency of CO_2 capture processes, with warmer and more humid environments enhancing the ability to capture CO_2. Consequently, the energy demand and associated costs of CO_2 removal vary with these climate-induced capture rates, highlighting the importance of considering climatic factors in the design and operation of carbon capture systems to optimize their efficiency and economic feasibility.	Science Paper	https://doi.org/10.1016/j.apenergy.2022.119895	Carbon Capture
BASF	2022	BASF and GS Engineering and Construction intend to jointly develop modular solutions for Carbon Capture	OASE blue solvent, developed by BASF in collaboration with RWE and Linde is characterized by the manufacturers as offering enhanced performance, lower energy requirements for regeneration, reduced degradation rates, and lower capital and operating costs. This technology, aimed at modular carbon capture solutions, is versatile for various flue gas sources, including coal-fired power plants, and focuses on cost savings and sustainability	Website	https://www.basf.com/global/en/media/news-releases/2022/09/p-22-358.html	Carbon Capture

Author	Date	Title	Key Points	Science Paper/ General Paper	Address	Category
Shen et al.	2021	Polychlorinated Biphenyl Emissions from Steelmaking Electric Arc Furnaces	SO$_2$ emissions from a specific German electric arc furnace (EAF) plant have been documented to range from 24 to 130 grams per tonne of liquid steel (g/t LS), showcasing the variance and the importance of adhering to best available techniques to control and minimize such emissions. The environmental impacts of EAF operations extend to the release of complex hazardous substances, including polychlorinated dibenzo-p-dioxins and furans (PCDD/F) and polycyclic aromatic hydrocarbons (PAHs). The reported emissions levels for PCDD/F from EAF stack emissions span from 0.07 to 0.9 micrograms International Toxicity Equivalents (µg I-TEQ) per tonne of liquid steel, whereas for PAHs, the emissions are benchmarked at 3.5 to 71 milligrams of EPA's 16 priority PAH compounds per tonne of liquid steel (Σ EPA16/t LS). Additionally, the inclusion of polychlorinated biphenyls (PCBs) emissions, particularly from the preheating phase of scrap steel processing in EAFs, into the UK's Multi-Media Emission Inventory under the Stockholm Convention, highlights the critical need for comprehensive monitoring and management strategies. These figures underline the complexities involved in the environmental management of steel production processes and the necessity for robust monitoring frameworks to effectively track and mitigate the release of these substances into the environment.	Science Paper	DOI:10.1007/s00128-021-03105-x	Carbon Capture
Air Quality Expert Group	January 2020	Impacts of Net Zero pathways on future air quality in the UK	1. The UK's carbon budget relies on CCS technologies despite uncertainties. 2. CCS aims to control emissions and reduce greenhouse gases, but the most effective CCS variant remains unclear. 3. A key concern with CCS is unintentional solvent and by-product emissions, particularly toxic species like nitrosamines. 4. New, less toxic CCS solvents are being developed, but regulatory processes should handle emissions and toxicity concerns during permitting.	Government Paper	MergedFile (defra.gov.uk)	Carbon Capture
Gemma Ralton	August 2021	New research shows how carbon capture technology can trap almost all emissions	The researchers highlighted that the study used a common amine solution called monoethanolamine for the CO$_2$ capture process which is used in many other CCS studies. However, it is expected that advanced solvents such as 2-aminomethylpropanol/piperazine and KS-1™ will result in lower energy requirements and reduced costs. Moving forward, the next steps will be to perform detailed case studies using these newer solvents to assess their effectiveness.	General article	New research shows how carbon capture technology can trap almost all emissions | Imperial News | Imperial College London	Carbon Capture
K. Zukuciova et al.	May 2020	Environmental Assessment of a Coal Power Plant with Carbon Dioxide Capture System Based on the Activated Carbon Adsorption Process: A Case Study of the Czech Republic	➢ *Carbon Capture Co-Benefits*: The results clearly demonstrate that the power unit with the connection of adsorption process leads to decreased environmental impacts. The study recognises reductions in SO$_2$ and NO$_x$ emissions due to carbon capture at coal power plants, contributing to reduced acidification and particulate matter formation. ➢ *Impact on Climate Change*: A 75% CO$_2$ capture rate from flue gases significantly reduces the climate change impact, with Scenario 2 showing a decrease due to the adsorption process. ➢ *Fuel Combustion Emissions*: Fuel combustion, particularly from brown coal, significantly influences the levels of potential environmental harm, with a high volume of volatile and persistent particulate matter affecting air quality. ➢ *Coal Quality*: The quality of brown coal, including its ash content and particle size, is crucial in controlling emissions and, consequently, the environmental impact. Further research on the chemical analysis of PM produced from brown coal combustion would be interesting. ➢ *Activated Carbon in CO$_2$ Capture*: The production of activated carbon from hard coal contributes to fossil depletion (however quantities are low (23kg/hr) in comparison to coal mined for combustion (214t/hr)). CO$_2$ emissions from natural gas combustion during activated carbon production are major environmental concerns (with climate change having the highest contribution of all the environmental impact categories at 99%). More research is required into alternative sources of activated carbon. ➢ *Environmental Impact Variability*: Different factors drive environmental impacts across sectors, with the power unit coupled with the adsorption process showing decreased impacts in several categories. ➢ *Economic Considerations*: The economic feasibility of carbon capture units (CCU) is linked to the purity of CO$_2$ produced, affecting the payback period and potential market price. *Potential for Sustainable Development*: Incorporating alternative sources like biomass for activated carbon production could reduce reliance on fossil fuels and aid in the transition to a low-carbon economy.	Science Paper	https://doi.org/10.3390/en13092251	Carbon Capture
Petrakopoulou et al.	2020	Impact of Climate Change on fossil fuel power-plant efficiency and water use	Explored the impact of rising ambient temperatures on the performance and water usage of natural gas and coal power plants. The study found that as ambient temperatures increase, there is a consequent rise in pressure at the steam turbine outlet. This increase in pressure adversely affects the efficiency of the plant, leading to decreased operational efficiency. The findings emphasize the vulnerability of power plant efficiency to changes in ambient temperatures, highlighting a critical challenge for the energy sector in the context of global warming and climate change.	Science Paper	https://doi.org/10.1016/j.jclepro.2020.122816	Carbon Capture
Hong et al.	2020	Low-Temperature Regeneration of Amines Integrated with Production of Structure-Controlled Calcium Carbonates for Combined CO$_2$ Capture and Utilization	Hong et al. (2020) conducted a study focusing on the behaviour of different amines, specifically MEA, DEA, MDEA, and 2-Amino-2-methyl-1-propanol (AMP), under various temperature conditions. The research aimed to provide insights into optimizing the amine regeneration process at lower temperatures. The study's findings contribute to understanding how each amine reacts to temperature variations, which is crucial for improving the efficiency and sustainability of the amine regeneration process in carbon capture technologies. By identifying optimal conditions for amine regeneration, the study aids in reducing energy consumption and operational costs, while minimizing the environmental impact of the carbon capture process.	Science Paper	https://doi.org/10.1021/acs.energyfuels.9b04339	Carbon Capture

Author	Date	Title	Key Points	Science Paper/ General Paper	Address	Category
B. Young et al.	December 2019	Comparative environmental life cycle assessment of carbon capture for petroleum refining, ammonia production, and thermoelectric power generation in the United States	***Environmental Impact Trade-offs:*** The installation and operation of CCS technologies result in an increase in particulate matter formation, eutrophication potential, and water consumption across all sectors per kg CO_2 abated. The effects on acidification potential and particulate matter formation potential are mixed, and the differences in trade-offs are primarily driven by the combustion emissions from fuel used to operate the capture unit, the supply chain for that fuel, and the relative impact of the carbon capture unit on baseline flue gas emissions. ***Reduction in Life Cycle Greenhouse Gases:*** The study details how carbon capture can lead to sector-wide reductions in life cycle greenhouse gases (GHGs). For example, applying CCS across all natural gas combined cycle (NGCC) plants can decrease national global warming potential (GWP) by 1.6%, albeit with an increase in other environmental impacts like photochemical smog formation potential (PSFP) and water consumption. ***Co-benefits from Carbon Capture:*** The analysis identifies possible co-benefits of carbon capture, especially the reductions in SO_2 and NO_x emissions from flue gas. In coal power plants, a significant percentage of life cycle emissions can be removed by the capture unit, leading to a net decrease in acidification potential (AP) and particulate matter formation potential (PMFP). However, in systems like ammonia production, petroleum refining, and NGCC, reductions in SO_2 at the capture unit are offset by increases in upstream fuel supply emissions. ***Complexity of CCS Viability:*** The study concludes that while amine-based post-combustion CCS can result in lower overall environmental impacts for thermoelectric power plants compared to other industrial operations, the commercial viability of CCS is complex and depends on technical, economic, and environmental factors.	Science Paper	https://www.sciencedirect.com/science/article/pii/S175058361830817X	Carbon Capture
Sign & Dhar / Beal et al.	2019	Overview of Carbon Capture Technology: Microalgal Biorefinery Concept and State-of-the-Art / Integrating Algae with Bioenergy Carbon Capture and Storage (ABECCS) Increases Sustainability	Algae-based carbon capture is an emerging approach distinct from traditional methods like CESAR-1 and OASE blue. Unlike conventional CCS methods that store CO_2 underground, algae, particularly microalgae, utilize CO_2 through bio-fixation. These algae are efficient in capturing CO_2, with rates ranging from 159-178 mg/L/day and up to 96% CO_2 consumption efficiency. This high efficiency is attributed to their ability to thrive in extreme environments and utilize waste gases such as CO_2, NO_x, and Sox from flue gas. Algae can be integrated into CCS systems, capturing CO_2 emissions from industrial sources and using them for growth, effectively removing CO_2 from the atmosphere.	Paper	https://doi.org/10.3389/fmars.2019.00029 / https://doi.org/10.1002/2017ef000704	Carbon Capture
Gunner Luderer et al.	November 2019	Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies	1. CCS is one of the technologies used in the power sector to mitigate carbon emissions. 2. SO_2 and NO_x emissions from fossil-based power production, including those using CCS, can contribute to PM_{10} formation and tropospheric ozone. 3. The power sector's contribution to PM_{10} and ozone primarily originates from the combustion of fossil fuels, including those utilizing CCS technology. 4. Direct emissions from fossil-based power production, including CCS, remain a significant source of air pollutants. 5. The impact of ionizing radiation, almost exclusively caused by nuclear power, is also discussed, and it is mentioned that this can be a factor in power generation.	Open access / Nature	https://www.nature.com/articles/s41467-019-13067-8	Carbon Capture
The London School of Economics	September 2019	Decarbonisation of the UK economy and green finance	1. Zero-Carbon Homes Reversal: The planned zero-carbon homes standard was revoked, raising concerns in the industry about the government's long-term commitment to decarbonising buildings. 2. Peterhead/Yorkshire White Rose CCS Program: Plans for a £1 billion fund for an advanced CCS scheme in either Peterhead, Scotland, or Yorkshire were scrapped. This decision hindered the development of the CCS market in the UK and eroded confidence in the private sector. The Committee on Climate Change (CCC) has stressed the importance of CCS in achieving net-zero emissions in the UK. These reversals also resulted in a lost economic opportunity, as the cancellation of the Peterhead CCS project could have created up to 600 jobs and fostered innovation in CCS technology, representing a missed chance for regional economic growth.	General paper	https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2019/09/Grantham-Research-Institute-response-to-inquiry-on-decarbonisation-of-the-UK-economy-and-green-finance.pdf	Carbon Capture
M. Aghaie et al.	November 2018	A systematic review on CO_2 capture with ionic liquids: Current status and future prospects	➢ *Promising Strategy*: ILs are considered a future-forward method for CO_2 capture due to their efficiency. ➢ *Absorption Mechanisms*: The review details how CO_2 is absorbed by ILs, including both practical and economic pros and cons. ➢ *Parametric Sensitivity*: CO_2 capture efficiency with ILs varies with different conditions and is analyzed through sensitivity studies. ➢ *Technical and Economic Challenges*: High costs, solvent degradation, and energy-intensive regeneration are major hurdles for current CO_2 capture methods. ➢ *Equation of State (EOS) Modeling*: PC-SAFT and PR EOS are effective models for predicting the behavior of CO_2/IL systems. ➢ *Cost of ILs*: The expense of functionalized ILs, which are better for CO_2 absorption, is significantly higher than conventional ILs. ➢ *Screening Criteria*: Guanidinium cations and fluorine anions show high CO_2 solubility, making them technically and economically favourable. ➢ *Commercialization:* To make IL-based CO_2 capture commercially viable, finding cost-effective IL/additive mixtures is crucial. *Challenges for Industrial Scale*: Overcoming issues related to ILs' high viscosity, cost, and availability is essential for developing efficient industrial CO_2 absorption systems.	Science Paper	https://www.sciencedirect.com/science/article/pii/S1364032118305100	Carbon Capture

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Flo et al.	2017	Results from MEA Degradation and Reclaiming Processes at the CO_2 Technology Centre Mongstad	The challenges associated with the monitoring and measurement of amines and N-amines stem from a global lack of standardized methodologies, creating complexities in accurately assessing their environmental and health impacts. Although some countries have embarked on specific monitoring initiatives, a unified international methodology remains absent. Notably, Norway's Technology Centre Mongstad (TCM) and Denmark's Esbjerg Power Station have adopted advanced techniques such as Fourier Transform Infrared Spectroscopy (FTIR) and Proton Transfer Reaction Mass Spectrometry (PTR-MS) for the detection and quantification of these compounds. These methods represent sophisticated approaches to monitoring, yet the disparity in practices across different countries highlights a significant gap in establishing a consistent framework for effectively tracking amines and N-amines globally. This inconsistency impedes the comprehensive evaluation of the environmental and health impacts posed by these substances, underscoring the necessity for the development and adoption of standardized monitoring methodologies worldwide.	Science Paper	https://doi.org/10.1016/j.egypro.2017.03.1899.	Carbon Capture
Sanz-Perez et al.	2016	Direct Capture of CO_2 from Ambient Air	Highlight the importance of improving the efficiency of amine absorption processes and the potential of amine-based sorbents in direct air capture (DAC) as strategies to significantly reduce greenhouse gas concentrations in the atmosphere, thereby contributing to global climate change mitigation efforts.	Science Paper	https://doi.org/10.1021/acs.chemrev.6b00173	Carbon Capture
Manzolini et al.	2015	Economic assessment of novel amine-based CO_2 capture technologies integrated in power plants based on European Benchmarking Task Force methodology	The degradation rates of different amines used in carbon capture technologies significantly influence the operational efficiency and cost-effectiveness of these systems. The amine solvent CESAR-1, which consists of 2-amino-2-methyl-propanol (AMP) and piperazine, demonstrates advantageous degradation characteristics. AMP, in particular, showcases approximately half the degradation rate compared to Monoethanolamine (MEA), a commonly used amine solvent. This reduced degradation rate means that AMP can remain effective for longer periods before needing replenishment, potentially lowering the overall operating costs associated with solvent replacement. Piperazine is also recognized for its chemical stability within the carbon capture process, contributing further to the durability and cost efficiency of the solvent mixture. Although the initial cost of these amines might be higher than that of MEA, their favourable degradation rates and stability can lead to reduced operational expenses over time, making CESAR-1 a potentially more economically viable option for long-term carbon capture applications.	Science Paper	https://doi.org/10.1016/j.apenergy.2014.04.066	Carbon Capture
Fernandez et al.	2014	Thermodynamic assessment of amine-based CO_2 capture technologies in power plants based on European Benchmarking Task Force methodology	CESAR-1, a carbon capture solvent, demonstrates a notable improvement in performance over traditional Monoethanolamine (MEA) in both coal and gas-fired power plants. The use of CESAR-1 results in a significant reduction in the power production penalty, which is the decrease in power output due to the energy consumption of the carbon capture process. For coal-fired plants, CESAR-1 reduces this penalty by 25%, and for gas-fired plants, by 12%, when compared to MEA. This efficiency is crucial in minimizing the impact of carbon capture on the plant's overall energy production and profitability. Additionally, CESAR-1 shows a lower rate of efficiency reduction over time, which suggests that it maintains its performance better than MEA. This improved efficiency and performance highlight CESAR-1's potential to enhance the feasibility and economic viability of carbon capture technology in reducing greenhouse gas emissions from power plants.	Science Paper	https://www.sciencedirect.com/science/article/pii/S0016236114002865	Carbon Capture
EEA	November 2011	Air pollution impacts from carbon capture and storage	1. Various scenarios related to CCS in the EU power generation sector were analyzed. 2. Implementing CCS in coal-fired power plants in Europe can significantly reduce CO_2 emissions. 3. CH_4 emissions increase due to additional coal mining required for CCS, depending on the source of this coal. 4. PM_{10} emissions decrease, driven by low emission factors in CCS-equipped power plants. 5. SO_2 emissions decrease significantly, although there's a slight increase due to additional shipping. 6. NO_x emissions remain similar but decrease when CCS is applied to coal, natural gas, and biomass power plants. 7. NH_3 emissions increase due to solvent degradation, but the overall impact is relatively small compared to other sources. 5. The impact of CCS implementation varies among EU Member States due to different emission factors and technological reasons. 6. The introduction of CCS can bring substantial benefits in reducing air pollutant emissions, particularly in Eastern and Southern European countries. However, uncertainties and challenges remain in the widespread adoption of CCS technologies.	Technical Report	Air pollution impacts from carbon capture and storage (CCS) — European Environment Agency (europa.eu)	Carbon Capture
Bobbink et al.	2010	Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis	A comprehensive global assessment has identified nitrogen accumulation as a critical factor impacting ecosystems worldwide, fundamentally altering species composition. This accumulation, primarily resulting from agricultural runoff, fossil fuel combustion, and industrial activities, leads to direct toxicity, soil acidification, and increased vulnerability to secondary stress factors such as drought and disease. These effects compromise ecosystem health and biodiversity, signalling an urgent need for strategies to manage nitrogen levels and mitigate their impacts on natural habitats.	Science Paper	https://doi.org/10.1890/08-1140.1	Carbon Capture
Knusden	2009	Summary Report: Amine Emissions to Air during Carbon Capture	Emissions of amine-based degradation products are of particular concern due to their toxic and carcinogenic properties at extremely low levels. Nitramines, though less potent than nitrosamines, are suspected carcinogens with a suggested longer lifetime in the atmosphere, potentially leading to higher exposure values. For a full-scale gas-fired power plant capturing 1 million tonnes of CO2 per year, the estimated amine emissions range from 40-160 tonnes per year. This level of emissions necessitates thorough investigation and management to mitigate potential environmental and health impacts.	Technical Report	https://nilu.no/wp-content/uploads/dnn/pp_14_2009_SR.pdf	Carbon Capture

Author	Date	Title	Key Points	Science Paper/ General Paper	Address	Category
CCS Norway	March 2023	Amine-based carbon capture produces small emissions of amines	1. Amine-based CO_2 capture facilities release small amounts of amine emissions into the air. 2. Amines can react with atmospheric substances to produce nitrosamines and nitramines. 3. Some of these compounds have shown carcinogenic effects in animal studies. 4. Environmental spread of these substances is considered unacceptable and should be minimized. 5. Norwegian environmental authorities use recommendations from the Institute of Public Health to establish emission limits for CO_2 capture facilities.	General article	Amine-based carbon capture produces small emissions of amines - Fullskala (ccsnorway.com)	Carbon Capture - Amine-Based Technologies
K. M. Jablonka et al.	January 2023	Machine learning for industrial processes: Forecasting amine emissions from a carbon capture plant	1. Amine-based carbon capture processes have environmental impacts, including solvent emissions into the atmosphere. 2. Interventions can have varied effects on solvent component emissions, especially when using mixtures of amines instead of single-component solvents like monoethanolamine. 3. Developing conventional process models to predict amine emissions is challenging due to a lack of relevant thermodynamic data on amines and limited understanding of emission mechanisms. 4. Plant operations are often far from a steady state, further complicating the modelling process. 5. Existing process models are considered too simplistic to handle the complexity of amine-based carbon capture systems.	Science paper	https://www.science.org/doi/10.1126/sciadv.adc9576	Carbon Capture - Amine-Based Technologies
H. Barros et al. (National Physical Laboratory)	August 2023	Research and Development Project Metrology for Post-Combustion Carbon Dioxide Capture using Amine-Based Technologies	➢ Carbon capture technologies like CCUS are used to extract and reduce CO_2 emissions from industrial installations. ➢ Amine-based CCUS, using chemical absorption into organic solvents, is widely used in power stations and natural gas processing facilities. ➢ MEA (Monoethanolamine) is a commonly used primary amine for CO_2 capture in PCC plants. ➢ Emissions and degradation of amines depend on operational parameters. ➢ Nitrosamines, potentially carcinogenic, can form during amine breakdown in PCC plants. ➢ Nitrosamine formation is linked to secondary amines, CO_2 loading, and temperature. ➢ Monitoring nitrosamines is essential for compliance with environmental regulations. *This project focuses on nitrosamines due to their toxicity and the need for standardized monitoring methods***.**	Report/Commercial	https://ukccsrc.ac.uk/wp-content/uploads/2023/09/Phase-1-WP2-Nitrosamines-metrology-on-stack-simulated-conditions-and-test-bench-laboratory-results.pdf	Carbon Capture - Amine-Based Technologies
N.C. Gupta et al.	February 2023	Assessment of the Impact of Various Amines on Micro- and Macro-organisms and their Potential Biodegradability in the Ecosystem	***Environmental Protection Contribution***: Amine-based capture facilities can significantly contribute to environmental protection and climate action by reducing air pollution and associated carbon emissions. Pre-treatment of flue gas in these facilities can remove 85 to 90% of CO_2, along with other harmful flue gas components like particulate matter, NO_x, and SO_2. ***Health Concerns from Amines***: The use of amines for CO_2 absorption has raised health concerns, although these are not fully understood. Research indicates that various amines and their degradation products could negatively impact human health, causing issues like irritation, sensitization, carcinogenicity, and genotoxicity. The severity of these impacts largely depends on the amount and type of amine emissions. ***Environmental Impact***: Once emitted into the air, amines and their degradation products can deposit in soil, water, or vegetation, potentially causing short-term or long-term detrimental effects on the ecosystem. Some amines may be readily degradable, while others persist in the environment. ***Lack of Comprehensive Studies***: There is a notable lack of comprehensive and systematic studies on the impacts of amines and their derivatives on various types of living organisms and ecosystems. The existing literature reviews the reported impacts, especially of nitramine and nitrosamine, on freshwater and marine fish, aquatic invertebrates, algae, cyanobacteria, bacteria, and terrestrial plants in terms of acute and chronic toxicity. ***Need for Systematic Studies***: There is a call for systematic studies on important amines and their degradation products emitted from post-combustion capture plants under different conditions. The goal is to understand the potential for toxic impacts and biotransformation in different regions with varying ecological and environmental conditions	Science Report	https://static1.squarespace.com/static/61a4d2a041902b6d99f6407d/t/63edfaf54e58f34cd5353b93/1676540665435/SCOPE+D3.2+Assessment+of+the+Impact+of+Various+Amines.pdf	Carbon Capture - Amine-Based Technologies

Author	Date	Title	Key Points	Science Paper/ General Paper	Address	Category
O.G. Brakstad et al.	February 2023	PNECs and degradation data for amines and amine degradation products	➢ Most solvent chemicals, including MEA and PZ, are considered readily biodegradable, non-bioaccumulative, and non-toxic according to PBT criteria. ➢ Primary and secondary amino and hydroxyl groups are more degradable than tertiary amines and compounds with quaternary carbon. ➢ Due to limited ecotoxicity data, especially chronic data, large assessment factors are used for deriving PNECs for amines. ➢ Acute ecotoxicity for degradation products is generally higher than for the solvents. ➢ Whole Effluent Toxicity and PBT assessment are recommended for the risk-based approach of produced waters. ➢ Nitrosamines are resistant to hydrolysis but degrade rapidly by photolysis, with degradation rates impacted by environmental factors. ➢ The environmental fate of nitrosamines in winter conditions (low temperatures and short days) shows higher half-lives compared to summer. ➢ Photolysis is a key degradation pathway for nitrosamines, with varying effects due to pH and dissolved organic carbon concentration. ➢ Most tested nitrosamines and nitramines are poorly biodegradable and are potential candidates for persistency. ➢ CESAR1 solvent (mixture of AMP and piperazine) showed higher EC50 for invertebrates than phytoplankton in ecotoxicity tests. ➢ According to the US EPA ECOTOX database, nitrosamines are more acutely toxic to phytoplankton than to invertebrates and fish	Science Report	https://static1.squarespace.com/static/61a4d2a041902b6d99f6407d/t/63dceeda92512e6528479327/1675423469233/SCOPE+D3.1+-+PNEC+and+degradation+data+and+pathways+for+amines+and+amine+degradation+products-2.pdf	Carbon Capture - Amine-Based Technologies
P. Pakchotanon et al.	February 2022	Atmospheric Dispersion of Gaseous Amine Emitted from Absorption-Based Carbon Capture Plants in Saskatchewan, Canada	➢ The study used the CALPUFF air pollution model, along with meteorological and geophysical data, to simulate the dispersion of gaseous amines. ➢ Ground amine concentrations were found to vary based on wind patterns, including wind direction and wind speed. ➢ The maximum allowable ground surface amine concentration standard is 15.2 µg/m3. ➢ Results demonstrated that using a water wash unit effectively reduced MEA concentrations, keeping them below the standard level. ➢ It is crucial for CO_2 capture plants in densely populated areas to incorporate water wash units to control amine emissions.	Science Paper	https://www.mdpi.com/1996-1073/15/3/1221	Carbon Capture - Amine-Based Technologies
NEA	September 2022	Carbon capture will halve emissions from Norcem Brevik	➢ Introduction of new components like amines results in pollution well below the Institute of Public Health recommendations for air and water. ➢ Close monitoring of drinking water sources is essential to detect any potential presence of amines. ➢ The release of aldehydes will result in concentrations much lower than occupational exposure limits. ➢ Aldehyde emissions are not expected to cause significant health effects.	General Article	https://www.carbonclean.com/blog/solvent-based-carbon-capture#:~:text=Amine%2Dbased%20solvents%20work%20in,to%20around%20120%20degrees%20Celsius.	Carbon Capture - Amine-Based Technologies
J. Hack et al.	October 2022	Review on CO_2 Capture Using Amine-Functionalized Materials	1. Amine scrubbing generates a significant amount of degraded solvent waste, making current scrubbing technologies energy-intensive and economically challenging. 2. Recent research has made considerable progress in CO_2 capture using amine-based solid materials, focusing on material synthesis, optimization, and mechanisms. 3. Challenges in the practical industrial application of amine-functionalized solid materials include long-term thermal stability during regeneration, oxidative degradation, and material fabrication with lower regeneration temperatures. 4. Lower regeneration temperatures (40-60°C) can enhance thermal stability and oxygen resistance, addressing issues related to thermal degradation. 5. Cost estimates support the reasonable adoption of CO_2 capture by amine-functionalized solid materials as an alternative to liquid amine scrubbing. The decisions and goals set at the 26th United Nations Climate Change Conference (COP26) are expected to reshape the research directions for CCS and CCU technologies, with amine-functionalized solid materials playing a significant role in achieving these objectives.	Science paper	https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9647976/#:~:text=Amine%20scrubbing%20produces%20a%20huge,and%20therefore%20not%20very%20economical.	Carbon Capture - Amine-Based Technologies
Envirotech	July 2022	Where Do Amine Emissions Come From?	1. The role of amines in the CCS industry is essential for reducing environmental impacts, but it can pose its own challenges. 2. Amine emissions primarily result from the CCS industry, where amine solvents can be released through airborne flue gases or wastewater effluent streams. 3. Amine emissions from CCS are considered extremely small and nearly negligible. 4. CCS, aimed at removing CO_2 from industrial flue streams, can potentially play a more significant role in amine emissions. 5. Amine solvents are emitted into the air via various processes like acid gas reactions, evaporation, oxidation, and thermal degradation, making gas analysis crucial in the industry's focus.	General article	https://www.envirotech-online.com/news/gas-detection/8/breaking-news/where-do-amine-emissions-come-from/58341	Carbon Capture - Amine-Based Technologies

Author	Date	Title	Key Points	Science Paper/ General Paper	Address	Category
M. Ellison et al. (National Physical Laboratory)	August 2022	Review of emissions from post-combustion carbon capture using amine-based technologies and current monitoring techniques	Key Points on Nitrosamine Monitoring for CCS Plants: ➢ Lack of suitable reference methods for monitoring nitrosamines in flue gas. ➢ Manual monitoring techniques using solid sample media or impingers are most suitable. ➢ Flue gas from CCS plants is likely saturated with water, requiring isokinetic sampling. ➢ Condensation in samples should be avoided to prevent losses and ensure representative results. ➢ Sample preservation is critical to prevent ongoing degradation in the sample media and during storage. ➢ Protection from sunlight is necessary to prevent the destruction of collected nitrosamines. ➢ Analysis of ambient air samples for nitrosamines is typically carried out using gas or liquid chromatography. ➢ Round-robin experiments indicate good agreement among different laboratories using varying methods for nitrosamine analysis. ➢ Developing an effective nitrosamine monitoring strategy for CCS plants is essential to address potential environmental and health concerns.	Report/Commercial	https://ukccsrc.ac.uk/wp-content/uploads/2023/02/Review-of-Emisions-from-Post-Combustion-Carbon-Capture-Using-Amine-Based-Technologies-and-Current-Monitoring-Techniques-August-2022-1.pdf	Carbon Capture - Amine-Based Technologies
S. Bull and J. Wilding	November 2022	Toxicological advice on air pollutants Hazard Ranking of Substances for Development of EALs for Substance Emissions to Air from Carbon Capture Technologies	➢ Post-combustion carbon capture (PCC) using amine-based systems is vital for reducing CO_2 emissions in the UK. ➢ Environmental permits are required for PCC installations to manage the impact on health and the environment. ➢ Amine-based systems emit small quantities of spent solvent and transformation products. ➢ The EA uses EALs to assess and mitigate operational risks. ➢ Operators must review scientific evidence to establish suitable EALs. ➢ The project aims to prioritize substances used in amine-based carbon capture technologies for the development of air EALs.	Report	https://ukccsrc.ac.uk/wp-content/uploads/2023/02/Prioritisation-of-carbon-capture-chemicals-interim-report_FINAL-1.pdf	Carbon Capture - Amine-Based Technologies
novoMOF	July 2022	Why MOFs outperform amine scrubbing?	➢ Amine scrubbing, originally developed in the 1930s to enhance natural gas quality by separating CO_2 and hydrogen, has been adapted for post- CCS. ➢ Amines, such as DEA, MDEA, Diisopropanolamine (DIPA), and Aminoethoxy Ethanol (Diglycolamine) (DGA), are commonly used as solvents due to their high CO_2 solubility and cost-effectiveness. ➢ The chemical absorption process with liquid amines involves CO_2 capture from flue gas, followed by regeneration of the CO_2-rich solvent in a stripper. ➢ While amine scrubbing is effective at capturing CO_2 (85-95% with high purity), it has drawbacks, including a high energy requirement for solvent regeneration, potential degradation of amines to toxic compounds, equipment corrosion, and environmental concerns. ➢ Alternative technologies, such as adsorption using Metal-Organic Frameworks (MOFs), show promise with lower energy consumption and improved thermal stability. ➢ Amine-modified MOFs have enhanced CO_2 capture capacity and can be regenerated at lower temperatures, making them a promising option for industrial applications.	Website article	https://blog.novomof.com/why-mofs-outperform-amine-scrubbing	Carbon Capture - Amine-Based Technologies
J. Orozco-Agamez et al.	July 2022	Effects of Composition, Structure of Amine, Pressure and Temperature on CO_2 Capture Efficiency and Corrosion of Carbon Steels using Amine-Based Solvents: a Review	➢ *High Efficiency and Selectivity*: Amine-based solvents, like MEA, DEA, and MDEA, are mature technologies for CO_2 absorption, offering efficiency of over 90% with high selectivity for different gas mixtures. ➢ *Energy Consumption*: These solvents generally require less energy for CO_2 capture compared to other technologies such as physical absorption or membrane processes. ➢ *Regeneration Capability*: The absorption process using amines is highly reversible, allowing for solvent regeneration and reuse, which is beneficial for industrial applications. ➢ *Corrosivity and Commercial Usage*: While amine solutions can be corrosive, mixed amines or polyamines like PZ and 4A1PPD tend to have lower corrosion rates, making them attractive for industrial use. ➢ *MDEA as a Conventional Solvent*: MDEA is highlighted for its low fugitive emissions, low regeneration heat requirement, and high CO_2 absorption capacity, making it suitable for natural gas processing under high pressures and CO_2 concentrations. *Reactions with CO_2*: Primary and secondary amines react directly with CO_2 to form carbamates, a reversible reaction that facilitates the regeneration of the amine solvent for continuous CO_2 absorption.	Science Paper	CET 96 (cetjournal.it)	Carbon Capture - Amine-Based Technologies

Author	Date	Title	Key Points	Science Paper/ General Paper	Address	Category
M. Lathouri et al.	November 2022	Human Health hazard assessment strategy for amine emissions around PCC facilities	➢ UV treatment and photolysis are effective degradation processes for nitrosamines and nitramines, especially important for nitrosamines in sunlight. ➢ Seasonal variations in temperature, sunlight, and hydrology influence nitrosamine and nitramine concentrations. ➢ Concentrations and temperatures significantly influence the biodegradability of chemicals in natural waters. ➢ According to the IARC, most nitrosamines are classified as possibly or probably carcinogenic to humans, while nitramines are less potent but still highly toxic. ➢ TD50 values, used for excess cancer risk calculation, indicate nitramines are much less carcinogenic than nitrosamines. ➢ Assessment factors should account for differences between animals and humans and variability among individuals. ➢ Sensitive populations, like infants and children, are more susceptible to the mutagenic effects of nitrosamines. ➢ Age-dependent adjustment factors (ADAFs) are important for estimating lifetime cancer risk. ➢ Gender differences also play a role in physiological responses to these compounds. ➢ NDMA and NMOR pose significant health risks, especially through dermal and inhalation exposure. Nitramines show moderate toxic health effects. ➢ QSAR models are useful for predicting the toxic activity and mutagenic properties of amines. ➢ Different organizations have set various public health thresholds for nitrosamines and nitramines. The Norwegian Institute of Public Health, for example, has recommended conservative exposure levels based on cancer risk estimates for NDMA.	Science Report	https://static1.squarespace.com/static/61a4d2a041902b6d99f6407d/t/6398474ee4765d458f4237a4/1670924112327/SCOPE+D3.3+Human+Health+hazard+assessment+strategy.pdf	Carbon Capture - Amine-Based Technologies
Carbon Clean	August 2021	The Role of Solvents in Carbon Capture	1. Common carbon capture solvents often include amines, like monoethanolamine (MEA). 2. APBS-CRDMax is a cost-effective solution when combined with the CDRMax chemical absorption process, reducing operational costs by up to 50%. 3. APBS-CARBex is a solvent using thermal energy to remove up to 50% CO_2 from biogas and landfill gas streams, widely proven for heavy industry applications.	General Article	The Role of Solvents in Carbon Capture (carbonclean.com)	Carbon Capture - Amine-Based Technologies
Environment Agency	November 2021	AQMAU recommendations for the assessment and regulation of impacts to air quality from amine-based post-combustion carbon capture plants	➢ AQMAU reviewed modelling techniques for air quality impacts from amine emissions in carbon capture plants. ➢ The ADMS module is the only commercially available modelling tool for such assessments. ➢ Recommendations include further experience, on-site measurements, validation exercises, and considering sensitivity to alternative modelling software and development. ➢ Amine emissions can lead to the formation of carcinogenic substances like nitrosamines and nitramines in the atmosphere. ➢ OH radicals play a crucial role in initiating atmospheric reactions for the formation of nitrosamines and nitramines. ➢ Various factors, including branching ratio, affect the formation of these compounds. ➢ Modelling tools like ADMS and others have been used for research purposes in this context. ➢ The report highlights knowledge gaps and provides recommendations for regulation and assessment. ➢ The fate of released substances, potential amine oxidants, and direct emissions of nitrosamines are key considerations. ➢ The saturation of flue gases with water in carbon capture plants requires isokinetic sampling. ➢ Protection from condensation, sample preservation, and sunlight are vital for accurate measurements.	Report	https://ukccsrc.ac.uk/wp-content/uploads/2021/11/AQMAU-C2025-RP01.pdf	Carbon Capture - Amine-Based Technologies
V. Buvik	2021	Stability of amines for CO_2 capture	➢ *Amine Degradation Management*: Advances in understanding oxygen solubility and amine structures help mitigate solvent degradation, which is crucial for cleaner CCS operations. ➢ *Monitoring and Air Quality*: Effective monitoring of amine health is essential, focusing on HSS concentrations and ammonia emissions to track air quality impacts. ➢ *Challenges in Measuring Degradation*: The lack of a single indicator for MEA degradation complicates air pollution monitoring from CCS processes. ➢ *Structural Stability and Air Emissions*: Structural modifications in amines can improve stability and reduce emissions, with CO_2 presence influencing degradation rates. ➢ *Novel Inhibitors*: Potassium iodide has been found to inhibit oxidative degradation in amines, potentially leading to reduced emissions in CCS. *Environmental Fate of Amines*: The environmental impact of amines, such as its effects on plant/soil systems, underscores the importance of managing these substances to protect air quality.	Doctoral thesis	https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/2777358/Vanja%20Buvik_PhD.pdf?sequence=1	Carbon Capture - Amine-Based Technologies

Author	Date	Title	Key Points	Science Paper/ General Paper	Address	Category
Xiaoxing Wang and Chunshan Song	December 2020	Carbon Capture from Flue Gas and the Atmosphere: A Perspective	1. Aqueous amine scrubbing is a widely used carbon capture technology but is energy-intensive. 2. The energy penalty for CO_2 removal is estimated at 0.2-0.5 MWh/ton-CO_2, equivalent to 20-30% of power plant output. 3. Absorbent regeneration and CO_2 recovery steps consume about 50% of the energy, mainly in the form of low-pressure steam. 4. This high energy penalty leads to increased capital and operating costs and corrosion issues with equipment. 5. Amine loss due to degradation and evaporation results in environmental pollutants. 6. The technology could raise electricity costs by 25-40%, limiting its widespread adoption. 7. Research is exploring alternative carbon capture methods, including absorption, adsorption, and membranes. 8. The goal is to develop more energy-efficient and cost-effective carbon capture technologies for the future.	Science paper	Frontiers | Carbon Capture From Flue Gas and the Atmosphere: A Perspective (frontiersin.org)	Carbon Capture - Amine-Based Technologies
International CCS Knowledge Centre	January 2020	Standardized Testing Eliminates Amine-Based CCS Barriers	1. Amines, water-soluble organic chemicals derived from ammonia, are used for CC due to their selective and reversible reactivity with CO_2. 2. Amine solvents may behave differently in various combustion sources due to differences in amine chemistry and gas stream makeup. 3. To address these variations, a portable testing apparatus (skid) is being developed by the Knowledge Centre to monitor amine behaviour. 4. Traditional carbon capture testing often occurs at a pilot-scale facility after product selection, but the skid allows for pre-selection testing of multiple amines. 5. The skid can be connected to various CO_2-containing gas streams, extending its applicability beyond coal-fired plants to other heavy-emitting industries. 6. Predicting amine behaviour can aid in selecting the right amine type for specific projects, benefiting multiple industry sectors seeking large-scale CO_2 reductions.	General paper	https://ccsknowledge.com/news/standardized-testing-eliminates-amine-based-ccs-barriers#:~:text=Amines%20are%20derivatives%20of%20ammonia,for%20more%20than%2020%20years.	Carbon Capture - Amine-Based Technologies
T. Spietz et al.	November 2020	Experimental results of amine emission from the CO_2 capture process using 2-amino-2-methyl-1-propanol (AMP) with piperazine (PZ)	1. Amines used in carbon capture processes can evaporate from the solution or be released as aerosols into the atmosphere. 2. Major components emitted with the treated gas include ammonia and AMP (amino methyl propanol). 3. CO_2 produced in the process contains traces of amine, ammonia, and formic acid. 4. Concentrations of other degradation products are below quantification limits. 5. Increasing the lean solvent temperature by 15 °C led to over a 50 ppm increase in AMP emissions, mainly in vapour form. 6. Introducing water at the top of the absorber effectively reduced amine emissions.	Science paper	https://www.sciencedirect.com/science/article/abs/pii/S1750583620305806	Carbon Capture - Amine-Based Technologies
T. Spietz et al.	2017	Nitrosamines and nitramines in Carbon Capture plants	➢ ***Amine Emissions and Their Environmental Impact:*** A small proportion of amine solvent and its degradation products escape from the absorber and are released into the atmosphere with cleaned flue gas. These compounds can adsorb to soil and potentially harm soil-dwelling organisms. If they become mobile and reach groundwater, they can contaminate drinking water sources. Studies have shown the formation of different products during amine-based CO_2 capture, including nitrosamines and nitramines. Some measurements are near or below the detection limit. ➢ ***Experimental Data on Emissions:*** The data from pilot plants, such as the Loy Yang pilot plant in Australia and the Maasvlakte pilot plant in the Netherlands, show varying concentrations of amine degradation products. Ammonia levels can be high due to intense MEA degradation. Nitrosamines, formaldehyde, and acetaldehyde are commonly measured MEA degradation products, with nitrosamine concentrations typically below 1 µg/m^3 in purified gas. ➢ ***Technology for Emission Reduction:*** Emission reduction methods can involve removing amines and their degradation products or limiting amine degradation through appropriate process parameters and solvent selection. Water wash systems are widely used as a means of reducing emissions, and acid-aqueous solutions or strong oxidants like potassium permanganate may be employed. Various technologies, including wet electrostatic precipitators, adsorbers, and condensers, can be used to reduce emissions. UV irradiation can help remove nitrosamines, but its effectiveness is influenced by factors like the colour of the solution and amine concentration. ➢ ***UV Irradiation and Ozone (O_3):*** UV irradiation can limit the concentration of nitrosamines in process wastes and water wash sections. Studies indicate that using both UV irradiation and O_3 can lead to the removal of about 90% of all N-nitrosamines. However, the effectiveness of ozone in destroying NDMA (N-nitrosodimethylamine) may be limited. Biological Methods: The use of biological methods is associated with long reaction times, and nitrosamines can be converted to nitroamines. ➢ ***Photolysis:*** *On sunny days, photolysis due to *OH radicals in the atmosphere can rapidly degrade nitrosamines, with varying lifetimes for different compounds.*	Science paper	https://intapi.sciendo.com/pdf/10.1515/oszn-2017-0027	Carbon Capture - Amine-Based Technologies

Author	Date	Title	Key Points	Science Paper/ General Paper	Address	Category
AECOM	2017	Net Zero Teesside –ES Air Quality Assessment of Amine Degradation Products	***Direct Emissions:*** ➢ The amine solvent used in carbon capture can degrade, leading to N-amines. ➢ Control factors include managing operating temperatures and reducing NO_2 emissions. ➢ Selective Catalytic Reduction (SCR) in the CCGT plant can help lower N-amine formation. ➢ Direct emissions of N-amines from absorber stacks are expected to be very low. ***Indirect Emissions:*** ➢ Most N-amines form post-release in the atmosphere. ➢ Formation depends on OH and NO_3 radicals, NO_x and O_3 concentrations, and amine types. ➢ Not all released amines will convert to N-amines. ➢ Photolysis removes NDMA from the environment. ***Conclusions:*** ➢ Assessments are conservative with uncertainties. ➢ Predicted air quality impacts are unlikely to exceed NDMA limits.	Report	https://infrastructure.planninginspectorate.gov.uk/wp-content/ipc/uploads/projects/EN010103/EN010103-001023-NZT%20DCO%206.4.8%20ES%20Vol%20III%20Appendix%208C%20Air%20Quality%20-%20Amine%20Degradation%20Assessment.pdf	Carbon Capture - Amine-Based Technologies
T. Spietz et al.	August 2017	Ammonia emission from CO_2 capture pilot plant using aminoethylethanolamine	➢ Amine-based CO_2 capture technology captures CO_2 from flue gas using a solvent. ➢ This process can result in the release of a small fraction of the solvent, leading to environmental concerns. ➢ The study investigates ammonia emissions from a pilot plant using a 40% aminoethylethanolamine solvent. ➢ It assesses the efficiency of a water wash unit and examines the impact of the lean amine temperature. ➢ The study also monitors emissions of other compounds such as SO_2, SO_3, NO_2, CS_2, and formaldehyde. ➢ Emissions from amines and amine degradation products are complex, especially with novel solvents.	Science Paper	https://link.springer.com/article/10.1007/s13762-017-1475-z	Carbon Capture - Amine-Based Technologies
K. Yu et al.	October 2017	Nitrosamines and Nitramines in Amine-Based Carbon Dioxide Capture Systems: Fundamentals, Engineering Implications, and Knowledge Gaps	➢ Nitrosamines and nitramines from CO_2 capture systems can harm the environment via stack emissions and disposal of used solvents. These emissions can affect nearby communities. ➢ Pollutants and Emissions: ➢ NO_x (NO and NO_2) drive the formation of nitrosamines and nitramines. ➢ Wash water units capture volatile contaminants but can sometimes add to nitrosamine sources. ➢ The choice of solvent amine affects pollutant formation. For instance, primary amine MEA mixed with tertiary amine N-methyldiethanolamine may reduce nitrosamine formation. ➢ Formation potential from amino acid salts isn't well-studied. ➢ Strategies include destroying nitrosamines in de-sorbers, enhancing wash water performance, and removing NO_x before CO_2 capture. ➢ High-temperature desorption and metal-based catalysts can mitigate nitrosamines. ➢ UV and ozone treatments can help in wash water systems. ➢ There's a need to study nitrosamine formation from amino acid salts. ➢ The effectiveness of wash water treatments and solvent development for low pollutant formation remain areas for research	Science Paper	https://pubmed.ncbi.nlm.nih.gov/28946738/	Carbon Capture - Amine-Based Technologies

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Process Ecology	February 2016	Health and Environmental Impacts of Amine-based CO_2 Capture Plant – A literature review	➢ ***Amine Emissions to Air:*** In amine-based CO_2 capture processes, most amine losses are released directly into the atmosphere. Without control technologies, entrainment and vaporization losses occur at the top of the absorber. Amine degradation products, largely influenced by impurities in the flue gas, are also released directly into the air. ➢ ***Water Wash Section:*** The use of a water wash section can significantly reduce amine and amine degradation product emissions to the air. It has been reported that implementing a water wash step is effective in minimizing amine losses. ➢ ***Complex Atmospheric Reactions:*** Amines released into the air undergo complex atmospheric reactions, leading to the formation of various compounds, including nitrosamines. A conservative 2% conversion rate from monoethanolamine (MEA) to nitrosamine has been used in worst-case studies. ➢ ***Fate of Amines:*** Amines and amine degradation products may eventually deposit into surface waters, posing potential risks to drinking water sources in the long term. ➢ ***Environmental Fugacity Study:*** An environmental fugacity study, using emission data from the literature and a 2% conversion rate from MEA to nitrosamine, indicated the potential risk to surface drinking water sources in Alberta near CO_2 capture facilities. This underscores the importance of emission control technologies to mitigate these risks. ➢ ***Highest Risk Compounds:*** Nitrosamine and nitramine degradation products are identified as posing the highest risk to human health and the environment in the context of CO_2 capture facilities. ➢ ***Lack of Plant Data:*** Despite the availability of literature, there is a significant lack of real plant data and online measurements related to amine emissions. This knowledge gap poses challenges for informed decision-making by companies and policymakers. ➢ **Recommendations:** Several recommendations are made, including the need for further studies to fill knowledge gaps, the development of control technologies to reduce amine emissions, investigations into the fate of amines released into the air, and the establishment of regulations for amine and amine degradation product emissions once sufficient data is available. ➢ ***Caution and Awareness:*** Given the uncertainties and risks associated with amine emissions, some reports recommend caution in building commercial amine-based CO_2 capture plants until knowledge gaps are addressed, which were not expected to be filled by 2020. ➢ ***Spatial Considerations:*** The report emphasizes the importance of considering the potential overlapping of amine emissions, including nitrosamines and nitramines emissions, in areas with multiple CO_2 emission facilities.	Report	https://processecology.com/articles/health-and-environmental-impacts-of-amine-based-co2-capture-plant-a-literature-review	Carbon Capture - Amine-Based Technologies
A. Rusin and K. Stolecka	February 2016	An Analysis of Hazards Caused by Emissions of Amines from Carbon Dioxide Capture Installations	➢ Amine-based post-combustion CO_2 capture is a prominent technology for coal-fired power plants. ➢ Monoethanolamine (MEA) is a common choice for CO_2 absorption due to its reactivity, cyclic capacity, and cost-effectiveness. ➢ Solvent degradation is a significant issue during CO_2 absorption, as amines can react with atmospheric oxidants (photo-oxidation) to produce toxic and carcinogenic compounds like nitrosamines, nitramines, and amides. ➢ The paper aims to establish safety limits for amine emissions and identify areas with hazardous amine concentration levels.	Science Paper	http://www.pjoes.com/pdf-61646-23718?filename=An%20Analysis%20of%20Hazards.pdf	Carbon Capture - Amine-Based Technologies
SEPA	August 2015	Review of amine emissions from carbon capture systems SEPA 2015	1. Amine solvents are used in carbon capture processes, and they can lead to the creation of new compounds during the process and after emission. 2. Nitrosamines and nitramines, which can form as a result, are potential carcinogens. 3. Environmental toxicity data for many of these compounds is limited, making their impact less understood. 4. EALs and Environmental Quality Standards (EQS) for most of these compounds are not established in the UK or EU. 5. Proposed thresholds for nitrosamines and nitramines in air from other countries may not align with UK standards. 6. Background levels of amines and their reaction products in the UK are unknown. 7. Sampling and analysing amine compounds, especially nitrosamines, is challenging and lacks standardized techniques. 8. Monitoring nitrosamines in ambient air around CCS processes is possible but currently difficult, requiring further method development.	Review report	https://www.sepa.org.uk/media/155585/review-of-amine-emissions-from-carbon-capture-systems.pdf	Carbon Capture - Amine-Based Technologies

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M. Azzi et al.	January 2014	Emissions to the Atmosphere from Amine-Based Post Combustion CO_2 Capture Plant - Regulatory Aspects	➢ Amine-based post-combustion carbon capture (PCC) technology is available to reduce CO_2 emissions from coal-fired power plants. ➢ The deployment of PCC can lead to reduced SO_x and NO_2 emissions from flue gases. ➢ However, the technology may produce other pollutants, including MEA, DEA, formaldehyde, acetaldehyde, acetone, methylamine, and amides, which have the potential to contribute to atmospheric pollution. ➢ Emissions of NH_3 and aerosols can be assessed using current air quality models to understand their impacts on air quality. ➢ Ongoing research is needed to develop chemical reaction schemes to describe the photo-oxidation of MEA emissions and other amines. ➢ Updates to air quality guidelines may be necessary to incorporate limits for NH_3, nitrosamines, and nitramines as more emission-related information becomes available.	Science Paper	https://www.researchgate.net/publication/259848629_Emissions_to_the_Atmosphere_from_Amine-Based_Post_Combustion_CO2_Capture_Plant_-_Regulatory_Aspects	Carbon Capture - Amine-Based Technologies
Gentry et al.	2014	What can be learned from natural analogue studies in view of CO_2 leakage issues in Carbon Capture and Storage applications?	Chronic inhalation of MEA vapours at high concentrations has been associated with neurological effects. Regarding carcinogenicity, extensive research on DEA has shown clear evidence of carcinogenicity in mice, suggesting an epigenetic mode of carcinogenesis involving intracellular choline deficiency.	Science paper	https://doi.org/10.1007/s00420-013-0900-y	Carbon Capture - Amine-Based Technologies
A. K. Morken et al.	2014	Emission results of amine plant operations from MEA testing at the CO_2 Technology Centre Mongstad	Extensive atmospheric emission monitoring was carried out at the CO_2 Technology Centre Mongstad (TCM DA) during amine-based post-combustion CO_2 capture using a mixed solvent system with monoethanolamine (MEA). Key findings from this monitoring campaign include: ➢ Low MEA Emissions: Atmospheric emissions of monoethanolamine (MEA), the primary solvent used in the process, remained consistently low and were detected in the ppb range. This suggests that MEA emissions were minimal. ➢ Undetectable Amine-Based Degradation Products: The atmospheric emissions of degradation products related to MEA, such as nitrosamines and nitramines, were found to be below detectable levels. This indicates that these potentially harmful compounds were not significantly released into the atmosphere. ➢ Ammonia Emissions: Emissions of NH_3 were detected but remained at low concentrations in the low parts per million (ppm) range. Ammonia emissions were present but did not appear to be a significant environmental concern. ➢ Alkyl Amine Emissions: Emissions of alkyl amines were also detected but at low concentrations in the low ppb range. Similar to ammonia, alkyl amine emissions were relatively low. Effectiveness of Absorber Wash Water: The report highlights that absorber wash water sections effectively reduced the potential atmospheric emissions associated with the amine-based solvent system. These sections appear to play a crucial role in minimizing emissions.	Science paper	https://core.ac.uk/download/pdf/82180895.pdf	Carbon Capture - Amine-Based Technologies
L. Zhu et al.	November 2013	Real-time monitoring of emissions from monoethanolamine-based industrial scale carbon capture facilities	***Amine Analysis in Carbon Capture (CC) Facilities:*** Appendix A The nature of amines in CC necessitates new analytical methods to monitor gas phase amines and their degradation products. Appendix B The largest CC testing facility at TCM in Norway employed two methodologies for emissions monitoring: FT-IR spectroscopy and Proton-Transfer-Reaction Mass Spectrometry (PTR-MS). Appendix C These methods allow real-time trace gas monitoring without the sample preparation needed in conventional methods. ***Using PTR-ToF-MS for Emission Monitoring:*** ➢ The PTR-ToF-MS setup at TCM allows monitoring of stack emissions. However, certain corrections to the signal might be required depending on industrial conditions. ➢ For optimal results, a dilution with dry zero air is recommended. ***Ammonia Emission Concerns:*** ➢ Ammonia is expected to be emitted from CC facilities as a major decomposition product of amines, especially monoethanolamine (MEA). ➢ The analytical technique must account for interference from ammonia, especially if it is present in large amounts. ➢ Using ammonium as the parent ion for proton transfer might be a solution due to its selectivity towards amines and nitrogen-bearing compounds. ***Carbon Dioxide Impact:*** ➢ Observations suggest a relation between CO_2 abundance and the MEA ion signal. ➢ The presence of high CO_2 content can interfere with certain measurements, such as acetaldehyde detection. This interference becomes a concern, especially during non-optimal operating conditions. For field conditions, a sample gas dilution of 1:10 is often sufficient, but high CO_2 concentrations (>5%) could make quantification of certain compounds challenging and necessitate corrections.	Science Paper	https://pubmed.ncbi.nlm.nih.gov/24215596/	Carbon Capture - Amine-Based Technologies

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A.D. Shah et al.	March 2013	Application of ultraviolet, ozone, and advanced oxidation treatments to wash waters to destroy nitrosamines, nitramines, amines, and aldehydes formed during amine-based carbon capture	The extraction of CO_2 from emissions involves chemicals like MEA (monoethanolamine) and PZ (piperazine) which can lead to the formation of hazardous byproducts. These byproducts can potentially be released into the atmosphere or water sources. **UV Treatment:** Ultraviolet (UV) radiation was effective in breaking down specific N-nitrosamines and N-nitramines. The extent of removal depended on the UV fluence (a measure of UV light intensity). For some compounds, changing the pH level could enhance removal. **Ozone Treatment:** Ozone, either alone or in combination with hydrogen peroxide (H_2O_2), was evaluated to treat amines and aldehydes, which don't significantly absorb UV light. Ozone was found to be more efficient than other treatments in breaking down amines. It was also efficient in destroying nitrite, another byproduct. Ozone requirements are significantly higher than standard levels used for drinking water treatment. However, using a two-stage wash water system could potentially reduce the amount of ozone required to levels comparable to drinking water treatment. **Combination of UV and Ozone:** A combination of UV and ozone treatments was explored. This combined approach takes advantage of the strength of each method, potentially providing better treatment outcomes at reduced costs. However, further research, including pilot evaluations, is needed to better understand the costs, efficiencies, and other factors associated with combining these treatments. **Laboratory Experiments:** Experiments were carried out using a laboratory setup to simulate wash water conditions. These experiments provided insights into the mechanisms of compound formation and removal. For instance, it was observed that NO_x gases could react with morpholine in the wash water to form nitrite and NMOR.	Science Paper	https://pubmed.ncbi.nlm.nih.gov/23425146/	Carbon Capture - Amine-Based Technologies
Ferraz et al.	January 2012	The impact of aromatic amines on the environment: risks and damages	Since these amines are potential carcinogenic agents and are discharged into the atmosphere, water and soil, they constitute an important class of environmental pollutants of enormous concern due to the potential for human exposure.	Science paper	https://pubmed.ncbi.nlm.nih.gov/22201924/#:~:text=Since%20these%20amines%20are%20potential,the%20potential%20for%20human%20exposure.	Carbon Capture - Amine-Based Technologies
C. J. Nielsen et al.	June 2012	Atmospheric chemistry and environmental impact of the use of amines in carbon capture and storage	➢ Reactions of emitted chemical compounds in the atmosphere are initiated by photolysis and reactions with oxidants such as OH and NO_3 radicals or ozone. ➢ Atmospheric box- and dispersion modelling is required to estimate concentration-time profiles and spatial distribution of target substances due to the complexity and interactions of these processes. ➢ OH radical reactions are likely the dominant sink for emitted amines and their degradation products in the atmosphere. ➢ Cloud droplets and wet particles play a critical role in the uptake of more soluble amines, preventing direct nitrosamine formation in the gas phase. ➢ Photolysis can be a major sink reaction for nitrosamines in both the gas and condensed phase, while amines and nitramines do not absorb light in the lower troposphere. ➢ NO_3 radical reactions with amines in the aqueous phase are slower compared to OH radical reactions. ➢ Current knowledge on the atmospheric chemistry of amines has increased significantly, especially due to interest in CCS. ➢ Proper assessment of environmental effects related to amine emissions should be based on solid process information from laboratory studies and modelled using appropriate methods.	Science Paper	https://pubmed.ncbi.nlm.nih.gov/22729147/	Carbon Capture - Amine-Based Technologies
A. Brekke et al.	2012	Environmental assessment of amine-based carbon capture	This report is part of the EDecIDe project's efforts to incorporate human and ecotoxicological effects into life cycle assessment (LCA) methodologies for carbon capture systems. It acknowledges that the findings presented in this report are preliminary steps in modelling human and ecotoxicological impacts from amine emissions, mainly focusing on methodology. ***Amine Emissions:*** Existing LCA methods seem to downplay the environmental impact of amine emissions from gas-fired power plants with carbon capture. It's unclear if this is because amine-related toxicological impacts are minimal or if other factors overshadow them.	Assessment Report	https://www.osti.gov/etdeweb/servlets/purl/22031472	Carbon Capture - Amine-Based Technologies
K. Veltman et al.	January 2010	Human and Environmental Impact Assessment of Post-combustion CO_2 Capture Focusing on Emissions from Amine-Based Scrubbing Solvents to Air	➢ *Freshwater Impact Score*: Well-characterized emissions of MEA and aquatic toxicity provide a reliable estimation for freshwater impacts. ➢ *Data Gaps*: Significant data gaps exist, particularly regarding the efficiency of the water wash and emissions of MEA degradation products. ➢ *Sensitivity Analysis*: Assumptions made about water-wash efficiency and aldehyde volatilization rates are critical. Lower water-wash efficiency significantly increases toxic impacts due to MEA emissions. ➢ *Aldehyde Emissions*: Increases in aldehyde emissions do not significantly affect total impact scores, suggesting current assumptions have a minor impact on overall results. ➢ *Non-Aquatic Toxicity Data*: There is a lack of comprehensive nonaquatic toxicity data for MEA, indicating a need for further research and better toxicity tests given the scale of potential releases. ➢ *Recommendations for CCS*: The study advises considering human health and environmental impacts when evaluating scrubbing technologies, not just greenhouse gas reduction potential. *Future Research Directions*: More experiments to determine degradation products and emissions of volatile compounds are needed, along with integrated assessments of environmental impacts, including emissions to water and soil.	Science Paper	https://pubmed.ncbi.nlm.nih.gov/20095561/	Carbon Capture - Amine-Based Technologies

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M. Lag et al.	April 2011	Health effects of amines and derivatives associated with CO_2 capture	1. Amines themselves are generally not harmful at typical concentrations found near power plants. 2. However, amines can participate in complex chemical reactions, forming compounds like nitrosamines and nitramines, which can pose health and environmental risks. 3. The health effects of many of these compounds are not well understood, but some are known to be highly carcinogenic. 4. Cancer risk depends on factors like the amount formed, released, atmospheric decomposition, and the carcinogenic potential of the substances. 5. Nitrosodimethylamine (NDMA) is identified as one of the most potentially carcinogenic compounds among them. 6. To assess cancer risk, the NIPH recommends using the risk estimate for NDMA for the total concentration of nitrosamines and nitramines in air and water. 7. The NIPH suggests maximum allowable levels to ensure minimal or negligible cancer risk from exposure to these substances, with a recommended limit of 0.3 ng/m³ for the total amount of nitrosamines and nitramines in the air.	Report	https://www.fhi.no/globalassets/dokumenterfiler/rapporter/2011/health-effects-of-amines-and-derivatives-associated-with-co2-capture.pdf	Carbon Capture - Amine-Based Technologies
M. Azzi et al.	May 2011	Potential impacts of emissions from amine-based CO_2 capture plants on the reactivity of surrounding air	➢ Atmospheric emissions from amine-based post-combustion carbon capture (PCC) systems differ significantly from those of conventional power plants. ➢ Gaseous amines and their degradation products can undergo atmospheric oxidation reactions, with implications for human health and the environment. ➢ Amine emissions may influence the formation of ozone, ammonia, secondary aerosols, and organic nitrogen compounds, affecting atmospheric chemistry, air quality, and ecosystems. ➢ Understanding the full scope of emissions from large-scale amine capture plants is a complex analytical challenge due to the diversity of amines and potential additives. ➢ Empirical models have been developed to predict pollutant concentrations, and air quality models are used to simulate spatial and temporal pollutant distribution in a given airshed. ➢ The dispersion of pollutants involves various mechanisms, including advection, atmospheric turbulence, and molecular-scale mass diffusion, with source location, terrain, and pollutant characteristics influencing downwind concentrations.	Conference Paper	https://ieaghg.org/docs/General_Docs/PCCC1/Abstracts_Final/pccc1Abstract00009.pdf	Carbon Capture - Amine-Based Technologies
Knudsen et al. (NILU)	March 2009	Summary Report: Amine Emissions to Air during Carbon Capture	➢ Amines themselves are not considered highly risky to human health and the environment. ➢ Amine emissions can contribute to nitrogen load and potentially lead to eutrophication in sensitive terrestrial ecosystems. ➢ The atmosphere can transform amines into various compounds, including nitrosamines, nitramines, aldehydes, and amides, which may pose risks to human health and the environment. ➢ Nitrosamines, in particular, can be toxic and carcinogenic even at very low levels. ➢ Nitramines are also concerning, albeit less potent as carcinogens than nitrosamines. ➢ Amine emissions can have both local and regional impacts, affecting the environment. ➢ Amine emissions may affect surface tension, which can influence rain formation and negatively impact the local environment. ➢ A worst-case study showed that predicted concentrations of photo-oxidation compounds from a generic amine plant are near proposed safety limits, suggesting potential risks to human health and the natural environment.	Report	https://nilu.brage.unit.no/nilu-xmlui/bitstream/handle/11250/2718655/08-2009-sk-mka-sr.pdf?sequence=1	Carbon Capture - Amine-Based Technologies
R. Shao and A. Stangeland	September 2009	Amines Used in CO_2 Capture - Health and Environmental Impacts	1. Amines used in CO_2 capture processes can pose health risks and environmental impacts. 2. Some amines and their degradation products may lead to negative effects on human health, such as irritation, sensitization, carcinogenicity, and genotoxicity. 3. Amines can also be toxic to animals and aquatic organisms, potentially causing eutrophication and acidification in marine environments. 4. The specific impacts depend on the types of amines used and the amount of amine emissions into the air. 5. Monoethanolamine (MEA), the most common amine in CO_2 capture, has relatively high biodegradability and poses no direct harm to human health, animals, vegetation, or water organisms. 6. Airborne emissions of nitrogen and ammonia from amine decomposition can contribute to eutrophication and acidification. 7. Other amines used in CO_2 capture, like AMP, MDEA, and PIPA, have lower biodegradability and more significant environmental impacts. 8. Amines, when emitted into the air, start degrading into various products, with nitrosamines having the most adverse environmental effects, including cancer risk, water contamination, and harm to aquatic life. These effects are considered a worst-case scenario at maximum amine emissions.	Report	https://bellona.org/assets/sites/3/2015/06/fil_Bellona_report_September__2009_-_Amines_used_in_CO2_capture-11.pdf	Carbon Capture - Amine-Based Technologies

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A. N. Rao and E. S. Rubin	October 2002	A technical, economic, and environmental assessment of amine-based CO_2 capture technology for power plant greenhouse gas control	➢ *CO_2 Capture Origins*: Initially for economic benefits in the 1970s, like enhanced oil recovery, rather than environmental concerns. ➢ *Commercialization*: The U.S. saw the first CO_2 capture plants in the late '70s for industrial uses. Norway began commercial CO_2 sequestration in 1996, which has since been under global scrutiny. ➢ *MEA-Based Absorption*: Dominant CO_2 capture method using Monoethanolamine (MEA), capturing 75-90% CO_2 and yielding over 99% pure CO_2 streams. ➢ *Impact on Plant Performance*: MEA integration impacts coal-fired plant operations, influencing emissions, performance, and carbon avoidance costs. ➢ *Emissions & Regulations*: Acidic impurities like SO_2 and NO_2 in flue gases can affect CO_2 capture efficiency and costs, with SO_2 having a more pronounced impact. ➢ *Capacity & Planning*: Amine-based CO_2 controls can lead to loss of plant capacity, affecting utilities' future capacity planning and technology choices. *Cost Variability & Research*: Ongoing research is crucial to reduce uncertainties in the cost and efficiency of carbon capture technologies.	Science Paper	https://pubmed.ncbi.nlm.nih.gov/12387425/	Carbon Capture - Amine-Based Technologies
Christina Andersen		Emissions and formation of degradation products in amine-based carbon capture plants	➢ In MEA-based carbon capture plants, ammonia is the main component emitted, accounting for a significant portion of the lost MEA. ➢ Ammonia is continually generated as an oxidative degradation product of MEA, and its emissions increase with higher O_2 concentrations in the flue gas. ➢ The presence of metal ions, such as iron, in the solvent can catalyse the formation of ammonia. ➢ Ammonia emissions primarily occur in the gas phase due to its high volatility. ➢ MEA also contributes substantially to overall emissions, with variations over time, potentially related to particle/mist formation. ➢ Emissions are influenced by factors like flue gas composition, solvent type, plant operation conditions (e.g., lean amine temperature), and the extent of corrosion. ➢ Water and acid wash treatments are applied to reduce emissions from the absorber tower. ➢ Emissions are affected by the CO_2 concentration in the flue gas, which impacts solvent pH. ➢ Lowering the water wash temperature temporarily reduced ammonia emissions but had no significant effect on MEA emissions due to the time required to reach a new equilibrium between volatile and dissolved ammonia. One step of water wash had little impact on ammonia emissions but significantly reduced MEA emissions, indicating that water wash primarily removed volatile MEA rather than sub-micron aerosols.	Technical report	https://forcetechnology.com/-/media/force-technology-media/pdf-files/5501-to-6000/5796-rapport-omkring-emissioner-fra-carbon-capture-final.pdf	Carbon Capture - Amine-Based Technologies
Global Cement and Concrete Association	-	Amine-based post-combustion capture	Despite the challenges, amine-based PCC is the most advanced carbon capture technology available to the cement industry with several suppliers on the market. Its planned commercial-scale deployment at Brevik – where waste heat from the cement manufacturing process will be used to optimise the process – is set to provide valuable operating experience to the industry, easing its future adoption by other cement plants.	General article	https://gccassociation.org/cement-and-concrete-innovation/carbon-capture-and-utilisation/amine-based-post-combustion-capture/	Carbon Capture - Amine-Based Technologies

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T. Xin et al.	October 2023	Process splitting analysis and thermodynamic optimization of the Allam cycle with turbine cooling and recompression modification	***Allam Cycle Overview:*** The Allam cycle is an advanced power cycle utilizing hydrocarbon fuels with nearly zero carbon emissions. In this cycle, oxy-fuel combustion products are directly mixed with the working fluid, and the turbine blade cooling is essential due to high cycle temperatures above 1,000°C. Heat integration may be applied to the Allam cycle to improve thermodynamic performance. ***Key Features of the Allam Cycle:*** The Allam cycle, developed in 2011, is a novel oxy-fuel supercritical CO_2 power cycle that captures nearly all CO_2 emissions from hydrocarbon fuels (natural gas or coal syngas) and features high efficiency. This cycle has garnered significant attention for its potential to reduce carbon emissions from fossil-fuelled power plants. ***Turbine Cooling and Recompression Modification:*** The Allam cycle involves turbine cooling, which requires diverting a portion of the recycled sCO_2 at low temperature into the turbine blades to dissipate heat. This study opts not to integrate the heat of the Air Separation Unit (ASU) due to increased complexity and inefficiency in matching the recuperator's heat requirements. Instead, a recompression modification measure is adopted, and a six-stage intercooling main air compressor is used to reduce the electricity consumption of the ASU. ***Thermodynamic Assessment Challenges:*** Conventional process simulation methods make it difficult to clearly understand the energy conversion from oxy-fuel combustion to electric power generation and the impact of turbine cooling and recompression on overall system performance. This study applies a splitting analytical method to the Allam cycle for thermodynamic evaluation and optimization. ***Thermal Cycle Splitting Analytical Method:*** The semi-closed Allam cycle is divided into two parts for analysis: the closed cycle (formed by the recycled sCO_2) and the open process (formed by fuel, oxygen, and combustion products). This method aids in understanding the energy conversion performance of the complex power cycle. ***Latent Heat Recovery and Power Generation:*** In the Allam cycle, most of the latent heat of the water is recovered to preheat the recycled sCO_2. The thermal energy of the fuel is calculated using the higher heating value (HHV). The fuel combustion heat drives both the closed cycle and the open process, and the cycle's electric power generation is considered for both processes. ***Net Efficiency Formulation:*** The net efficiency of the Allam cycle is formulated as a function of the net power output, the thermal energy of natural gas, and the efficiencies of the closed and open cycles, including the efficiency penalty of the ASU. ***Simulation Models and Parameters:*** The thermodynamic performance of the real cycles, including the semi-closed cycle, closed cycle, simple cycle, and modified cycle with recompression. ***Net Efficiency of the Allam Cycle:*** The net efficiency of the Allam cycle is calculated based on the share ratio of the natural gas combustion heat used for the closed cycle and open process, the efficiency penalty of the ASU, and the thermal energy of the natural gas combustion.	Science Paper	https://www.sciencedirect.com/science/article/pii/S0360544223028529	Allam Cycle

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H. Yu et al.	December 2020	Optimal liquified natural gas (LNG) cold energy utilization in an Allam cycle power plant with carbon capture and storage	***Allam Cycle and LNG Integration:*** The Allam cycle, a promising oxy-combustion power cycle, is efficient and cost-effective for power generation and achieves near-zero emissions. Integrating LNG cold energy in the Allam cycle can reduce the compression work required for the carbon capture process and recycled flue gas, improving energy efficiency. This study investigates different ways to utilize LNG cold energy in both standalone power plants and cogeneration systems. ***CCS in Power Plants:*** Carbon capture and storage is critical in mitigating climate change. The power sector is responsible for a significant portion of global greenhouse gas emissions, and reducing CO_2 emissions in power plants is both technically and economically challenging. ***Allam Cycle Description:*** The Allam cycle is a low-pressure ratio Brayton cycle using high-pressure recirculating CO_2 as the working fluid. Oxygen from the Air Separation Unit (ASU) is pressurized and heated before being fed into the combustor, where it mixes with recycled flue gas and fuel. After expansion through a turbine, the low-pressure flue gas preheats various streams in heat exchangers. Most flue gas is recompressed and recycled, while the rest is processed for carbon capture and storage. ***Captured Flue Gas Treatment:*** Captured flue gas can be compressed or liquefied by refrigeration systems and then pumped for transportation and storage. Liquefaction requires significantly less work than compression. LNG cold energy can be used as an efficient refrigeration system, integrated with different zones of the Allam cycle depending on LNG availability. ***Process Simulation and Optimization:*** The study uses Aspen HYSYS for process simulation, optimizing different system configurations with a Particle Swarm Optimization (PSO) algorithm. This approach helps determine the best operational conditions for the Allam cycle integrated with LNG cold energy utilization. ***Standalone Power Plant Analysis:*** The study examines the flue gas condensation and LNG evaporation processes, finding that the flue gas condensation heat decreases with increased pressure, as does the evaporation heat of LNG. There is a trade-off between the CO_2 liquefaction process and the natural gas compression process, with the Allam cycle requiring high-pressure natural gas and corresponding significant compression work. ***Cogeneration System Analysis:*** For cogeneration systems, the recycled flue gas is integrated with a large flowrate LNG stream. This integration can save substantial compression work. The study indicates that 94.45% of the recycled flue gas can be liquefied, significantly reducing the required compression work. The introduction of an Organic Rankine Cycle (ORC) in the system can further improve efficiency by converting some of the recycled flue gas condensation heat into electricity and reducing compression work.	Science Paper	https://www.sciencedirect.com/science/article/pii/S0196890420312498	Carbon Capture / Allam Cycle
R. Scaccabarozzi et al.	June 2016	Thermodynamic analysis and numerical optimization of the NET Power oxy-combustion cycle	***NET Power Cycle Analysis and Optimization:*** The study presents a comprehensive thermodynamic analysis and optimization of the NET Power (Allam) cycle. It uses an Aspen Plus flowsheet with accurate models of the main equipment units, including a cooled turbine, and an equation of state for fluid properties. The study aims to maximize the cycle's net electric efficiency and assess the impact of modelling assumptions and equipment performance on cycle variables and efficiency. ***Oxy-combustion Technology for Carbon Capture:*** The NET Power cycle employs oxy-combustion technology, where fuel is burned with pure oxygen instead of air. This process significantly reduces the nitrogen content in flue gases, enhancing CO_2 concentration and reducing the energy intensity of CO_2 separation, making it a promising mid-term solution for electricity production from natural gas with carbon capture capabilities. ***Cycle Efficiency and Comparative Analysis:*** The NET Power cycle has been estimated to achieve a cycle efficiency of 59% for a single combustor scheme and about 57.5% for a double combustor scheme. The International Energy Agency (IEA) Green House Gas program's report compares various oxy-combustion cycles, finding the NET Power cycle to be the most promising both in terms of efficiency and economics, with the lowest cost of electricity (COE) and high net electric efficiency. ***Cycle Description and Component Analysis:*** The NET Power cycle uses almost pure oxygen (99.5% purity) pressurized at 120 bar, mixed with recycled CO_2 preheated in a regenerator, and sent to the combustor. The combustor operates between 200 and 400 bar with a controlled firing temperature. The cycle efficiently recovers heat from flue gases using a multi-flow heat exchanger (regenerator), condenses and separates water, and recycles CO_2 back to the combustor. The cooling medium temperature, power consumption of the air separation unit, regenerator effectiveness, and turbine cooling system effectiveness significantly influence the cycle efficiency. ***Cycle Modelling in Aspen Plus:*** The NET Power cycle model was developed in Aspen Plus V8.4. Specialized models were required for the turbine and the regenerator due to the real gas mixtures used in the cycle. The turbine model needed to include appropriate equations of state to accurately represent fluid behaviour and required only a few calibration parameters, given the undisclosed geometrical details of the stages.	Science Paper	Thermodynamic analysis and numerical optimization of the NET Power oxy-combustion cycle - ScienceDirect	Allam Cycle

Author	Date	Title	Key Points	Science Paper/ General Paper	Address	Category
Local Government Association	November 2022	Neighbourhood approach to decarbonisation	It discusses aspects related to community engagement, funding challenges, monitoring, and evaluation in the context of local decarbonisation efforts.	General paper / open access	https://www.local.gov.uk/publications/neighbourhood-approach-decarbonisation	General
Elisa Papadis, George Tsatsaronis	August 2020	Challenges in the decarbonization of the energy sector	***Overview of Amine-Based CO_2 Capture Systems:*** ➢ The concept of CO_2 separation from flue gas began in the 1970s, initially aimed at economic uses such as enhanced oil recovery (EOR) rather than environmental concerns. ➢ Commercial CO_2 capture plants have utilized monoethanolamine (MEA) based solvents, with capture efficiencies between 75% to 90%, resulting in a nearly pure CO_2 product stream. ***Process Description:*** ➢ CO_2 capture from flue gas involves a continuous scrubbing system with an absorber and a regenerator, where CO_2 is removed and concentrated, and the solvent is recovered. ➢ The process demands significant heat for solvent regeneration, typically sourced from the steam cycle, which reduces the net efficiency of the power plant. ***Interactions with Other Air Pollutants:*** ➢ Amine systems interact with other air pollutants, particularly SO_2 and NO_x. SO_2 and NO_2 react with MEA, forming heat-stable salts that impede CO_2 absorption, necessitating low concentrations of these gases to reduce solvent loss. ***Process Performance Model:*** ➢ CO_2 removal efficiency is influenced by parameters affecting gas-liquid equilibrium such as flow rates, temperature, pressure, flue gas composition, CO_2 concentration, MEA concentration, and absorber design. ***Characterization of Uncertainties:*** ➢ A stochastic simulation approach is used in the model to account for the uncertainty and variability in design parameters, reflecting the current literature and data from process developers. ***Model Outputs:*** ➢ Outputs include the MEA requirement, energy requirements, and environmental emissions. The energy requirements, which contribute to the total amine system energy requirement, are crucial as they dictate the net power output and the cost of CO_2 avoidance. ***Process Cost Model:*** ➢ The cost model integrates with the process performance model, considering capital cost, operating and maintenance costs, as well as the cost of electricity and CO_2 avoided. ➢ Capital costs are influenced by the flow rate of flue gas and the mass flow rate of CO_2, while operating costs are affected by the energy required for solvent regeneration and CO_2 compression. ***Cost of CO_2 Avoided:*** There is a distinct difference between the cost per tonne of CO_2 removed and the cost per tonne of CO_2 avoided, due to the energy-intensive nature of amine scrubbers. The latter metric is based on net plant capacity and is a crucial financial indicator for environmental control systems	Science Direct	https://www.sciencedirect.com/science/article/pii/S0360544220311324	General
Neil Jennings, Daniela Fecht and Sara De Matteis	March 2019	Co-benefits of climate change mitigation in the UK: What issues are the UK public concerned about and how can action on climate change help to address them?	➢ Governments are challenged with reducing greenhouse gas emissions while addressing various objectives like improving public health and reducing unemployment. ➢ There are multiple co-benefits associated with climate change mitigation, which are not always fully considered in policy and decision-making. These benefits include enhanced public health, reduced NHS costs, improved energy security, growth in the low-carbon job market, and a reduction in poverty and inequality. ➢ Cities and devolved administrations are well-positioned to leverage these co-benefits because they often manage relevant budgets (e.g., health, transport, housing) and understand the interconnectedness of various policy priorities. ➢ To achieve faster and more significant reductions in greenhouse gas emissions, it's essential that public sector decision-making takes these co-benefits of climate change mitigation into account.	Science Paper / Imperial College London	https://www.imperial.ac.uk/media/imperial-college/grantham-institute/public/publications/briefing-papers/Co-benefits-of-climate-change-mitigation-in-the-UK.pdf	General
C. Gerbaulet et al.	March 2019	European electricity sector decarbonization under different levels of foresight	***Decarbonisation Targets and Foresight Impact:*** The European Union aims to substantially reduce carbon intensity in its electricity generation as part of the European Roadmap 2050. The study uses a model (dynELMOD) to analyze the impact of foresight on investment decisions in the electricity sector. It finds that incorporating climate targets makes additional fossil fuel investments uneconomic from 2025, leading to a phase-out of coal and natural gas in the 2040s. Limited foresight results in stranded fossil fuel investments in the 2020s, while a CO_2 budgetary approach leads to sharper emission reductions before 2030, lowering overall costs. ***Emission Reduction Targets:*** Europe has set stringent targets for low-carbon energy transformation, aiming for a 40% greenhouse gas emission reduction by 2030 (based on 1990 levels) and an 80-95% reduction by 2050. This involves a combination of fossil fuels (some with carbon capture), nuclear power, and renewable energy sources. ***Scenario Analysis:*** The paper evaluates different pathways for decarbonising the electricity sector by 2050, considering various levels of foresight, such as perfect foresight, myopic foresight, and a budgetary approach where CO_2 emissions can be allocated freely from 2020 to 2050.	Science Paper	https://www.sciencedirect.com/science/article/pii/S0960148119302538	General (Decarbonisation)

Author	Date	Title	Key Points	Science Paper/ General Paper	Address	Category
Schmitz et al. / Dirnböck et al.	2019 / 2018	Responses of forest ecosystems in Europe to decreasing nitrogen deposition / Currently legislated decreases in nitrogen deposition will yield only limited plant species recovery in European forests	Even with documented decreases in nitrogen deposition, recent studies highlight a concerning trend: limited responses in key indicators of ecosystem health, such as soil solution nitrate concentrations, understory vegetation diversity, tree growth rates, and overall tree vitality. These findings suggest that simply reducing nitrogen deposition may not be sufficient to foster significant recovery in ecosystems already burdened by accumulated nitrogen loads. This situation underscores the need for a more holistic approach to environmental management, one that also takes into account the effects of climate change and incorporates sustainable forest management practices. Such an approach would aim not only to address the immediate impacts of nitrogen deposition but also to mitigate long-term accumulated effects, ensuring healthier and more resilient ecosystems.	Science Paper	https://doi.org/10.1016/j.envpol.2018.09.101 / http://doi.org/10.1088/1748-9326/aaf26b	General (Decarbonisation)
L.G Echeverri	March 2018	Investing for rapid decarbonization in cities	***Opportunities for Decarbonisation in Cities:*** Cities offer significant opportunities for decarbonisation, especially in sectors like buildings, transportation, water, and waste management. Systemic transformations in these areas are crucial to meet the Paris Agreement's target of keeping global temperature rise below 2°C, considering the urban population is growing by approximately 1.4 million weekly. However, significant barriers exist to the pace of investment needed in these sectors. ***Cities' Role in Carbon Dioxide Emissions:*** Cities are currently responsible for more than 70% of CO_2 emissions. With an additional 2.5 billion urban residents expected by 2050, cities are both the best opportunity and the greatest challenge for decarbonisation. ***Infrastructure Investment Needs:*** Between 2015 and 2030, more infrastructure is expected to be built globally than the existing infrastructure at the start of this period. This translates to a need for approximately $90 trillion in new investments, with over 70% of these investments categorized as urban infrastructure investments. The current annual level of investments is estimated to be around $2.5 to $3 trillion, which is lower than the estimated need of $4.1 to $4.3 trillion. ***Trends in Global Energy Investment:*** The International Energy Agency (IEA) reported that global energy investment is not yet consistent with the transition to a low-carbon energy system as envisioned in the Paris Agreement. Investments in solar PV, electric vehicles, and wind are on a promising trajectory, but other technologies like CCS have not been seen as robust investments. About 70% of power generation investments in 2015 went to renewable energy, and 12% of global energy investments were directed toward energy efficiency, particularly in city infrastructure. ***Future Investment Needs and Projections:*** The IEA projects a need of approximately $44 trillion USD in investments in energy supply by 2040, with 20% allocated to renewable energy. However, this investment level is not sufficient for the Paris Agreement's less than 2°C target. Additional investments in renewable energy and energy efficiency are required. The nexus between energy and water demands in urban areas is also highlighted, underscoring the increased energy needs linked to rising urban populations and water demand.	Science Paper	https://www.sciencedirect.com/science/article/pii/S1877343517301240	General (Decarbonisation)
J.H. Wesseling et al.	May 2017	The Transition of Energy Intensive Processing Industries Towards Deep Decarbonization	***Iron and Steel Sector Innovations:*** ➢ Energy Efficiency (I/R): Implementing best available technologies like steam motor heat pumps and combined heat and power systems. ➢ Material Efficiency & Recycling (I/R): Reducing primary material intensity and improving product design and recycling. ➢ CCS (I/R): Integrating CCS into process design, which can be incremental but may need significant additional space and technology for integration. ➢ Recirculating Blast Furnace & CCS (R): Needs high integration into existing plants and infrastructure for CO_2 transport. ➢ Smelt Reduction & CCS (RR): Makes conventional coke ovens and blast furnaces obsolete. ➢ Direct Reduction with H2 (RR): Requires hydrogen supply infrastructure. ➢ Electrowinning (RRR): Makes conventional steelmaking processes obsolete but is only available at lab scale. ***Aluminium and Chemicals Sector Innovations:*** ➢ Advanced (Inert) Anodes (I): Avoids oxidation and CO_2 emissions. ➢ Advanced Steam Crackers & CCS (I): Involves advanced furnace materials, gas turbine integration, and use of membrane technology for separation and catalytic cracking. ***Glass and Cement Sector Innovations:*** ➢ Electro-plastics (I/R; RR): Requires conversion to bio or electricity-based feedstocks and integration into existing plants. ➢ Electric Melting (I/R): In use but scalability and process changes need clarification. ➢ Geopolymers (RR): Needs different input materials and may have different material characteristics and costs. ***Paper & Pulp and Biorefineries Sector Innovations:*** ➢ Separation and Drying Technologies (I/R): Key to reducing energy intensity for carbon-neutral operation. Biorefinery Development (RRR): Potentially replaces existing petro-refineries by providing bio-based chemicals and feedstock.	Science Paper	https://www.sciencedirect.com/science/article/pii/S1364032117307906	General (Decarbonisation)

Author	Date	Title	Key Points	Science Paper/ General Paper	Address	Category
Van de Berg et al.	2016	Evidence for differential effects of reduced and oxidised nitrogen deposition on vegetation independent of nitrogen load	The form of nitrogen deposition, whether reduced (ammonia, NH_3) or oxidized (nitrate, NO_x), plays a critical role in determining its impact on various habitat types. Research indicates that acid and mesotrophic grasslands exhibit higher sensitivity to reduced forms of nitrogen, whereas calcareous grasslands and woodlands are more adversely affected by oxidized nitrogen. This differential response highlights the nuanced relationship between nitrogen deposition and ecosystem health, emphasizing the importance of considering both the form of nitrogen and the specific characteristics of each habitat when assessing the impact on biodiversity.	Science Paper	https://doi.org/10.1016/j.envpol.2015.09.017	General (Decarbonisation)
M. Davies & T. Oreszczyn	March 2012	The unintended consequences of decarbonizing the built environment: A UK case study	***Focus on the UK's Decarbonisation Efforts:*** The paper emphasizes the need for developed countries, like the UK, to significantly reduce GHG emissions, particularly in the built environment and housing sectors. ***Potential for Unintended Consequences:*** The study highlights the complexity of decarbonising the built environment and the potential for significant unintended consequences. These could arise due to the interconnectedness and complexity of the processes involved in decarbonising housing and other built environments. ***Need for Multidisciplinary Collaboration:*** The paper stresses the urgent need for forming multi- and interdisciplinary teams with diverse skill sets, including building physicists, engineers, economists, epidemiologists, statisticians, behavioural scientists, complexity scientists, and policymakers. This collaborative approach is crucial to address the challenges effectively. ***Importance of Coordinated Research and Policy Making:*** The document argues that without a coordinated and concerted program of relevant research, it is difficult to formulate and implement necessary policies effectively. There is a concern about the potential for enormous and irreversible mistakes in the absence of such an approach.	Science Direct	https://www.sciencedirect.com/science/article/pii/S0378778811005068	General (Decarbonisation)